



**VALUES OF THE EULER AND CARMICHAEL FUNCTIONS
WHICH ARE SUMS OF THREE SQUARES**

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Abstract

Let φ denote Euler's totient function. The frequency with which $\varphi(n)$ is a perfect square has been investigated by Banks, Friedlander, Pomerance, and Shparlinski, while the frequency with which $\varphi(n)$ is a sum of two squares has been studied by Banks, Luca, Saidak, and Shparlinski. Here we look at the corresponding three-squares question. We show that $\varphi(n)$ is a sum of three squares precisely seven-eighths of the time. We also investigate the analogous problem with φ replaced by Carmichael's λ -function. We prove that the set of n for which $\lambda(n)$ is a sum of three squares has lower density > 0 and upper density < 1 .

1. Introduction

Let $\varphi(n)$ denote Euler's totient function, defined as the size of the unit group $(\mathbf{Z}/n\mathbf{Z})^\times$. A theorem of Banks et al. [2, pp. 40, 43] asserts that for any $\epsilon > 0$ and all large x ,

$$x^{0.7038} \leq \#\{n \leq x : \varphi(n) = \square\} \leq \frac{x}{L(x)^{1-\epsilon}}, \quad (1)$$

where

$$L(x) = \exp(\sqrt{\log x \log \log \log x}).$$

We write " \square " here and below to denote a generic member of the set $\{n^2 : n = 0, 1, 2, 3, \dots\}$ of perfect squares. The same authors present a heuristic argument that the left-hand side of (1) can be replaced with $x^{1-\epsilon}$. An investigation into the corresponding question for sums of two squares appeared the following year, where it was shown [4, p. 124, eq. (1)] that

$$\#\{n \leq x : \varphi(n) = \square + \square\} \asymp \frac{x}{(\log x)^{\frac{3}{2}}}. \quad (2)$$

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(Recall that “ $F \asymp G$ ” means that the ratio F/G is bounded between two positive constants.) This may be compared with the theorem of Landau [11] that as $x \rightarrow \infty$,

$$\#\{n \leq x : n = \square + \square\} \sim \left(\frac{1}{\sqrt{2}} \prod_{\substack{p \equiv 3 \pmod{4} \\ p \text{ prime}}} \left(1 - \frac{1}{p^2}\right)^{-\frac{1}{2}} \right) \frac{x}{(\log x)^{1/2}}.$$

See [15] for an extended discussion of Landau’s theorem and its generalizations, and see [20, pp. 183–185] for what seems to be the most elementary proof.

What about sums of three squares? (By a theorem of Lagrange, every positive integer is a sum of four squares, so this is the last interesting case.) The natural numbers which are sums of three squares are characterized by a theorem of Legendre: $n = \square + \square + \square$ precisely when n is *not* of the form $4^k(8l + 7)$, where k and l are nonnegative integers (see, e.g., [21, Appendix to Chapter IV]). A straightforward consequence of this characterization is that about 5/6 of all natural numbers up to x are expressible as a sum of three squares, once x is large. The error term in this approximation is easily seen to be $O(\log x)$, but as discussed in [22] and [17], it displays somewhat complicated pointwise and average behavior. Our first result is the determination of the density of n for which $\varphi(n) = \square + \square + \square$.

Theorem 1. *The set of n for which $\varphi(n)$ is a sum of three squares has asymptotic density 7/8. More precisely, for $x \geq 2$, we have*

$$\#\{n \leq x : \varphi(n) = \square + \square + \square\} = \frac{7}{8}x + O\left(\frac{x}{(\log x)^{3/10}}\right). \tag{3}$$

It seems amusing that for $k = 1, 2$, and 3 , the odds that $\varphi(n)$ is a sum of k squares are alternately higher, then lower, then higher, than the corresponding odds that n is a sum of k squares. One can anticipate a possible objection to these comparisons: Since $\varphi(n)$ is even for $n > 2$, we should compare $\varphi(n)$ only with even m . An even number m is a sum of three squares with probability 11/12, and so $\varphi(n)$ is *less* likely to be a sum of three squares than its even brethren. This is all true, but we can respond as follows: $\varphi(n)$ is almost always a multiple of 4 (since almost every n has at least two different odd prime divisors), and a multiple of 4 is a sum of three squares with probability 5/6. Our hypothetical detractor can then counter by suggesting we consider multiples of 8 (where the probability is again 11/12), to which we counter with multiples of 16 (where it is 5/6), etc. In any case, the objection highlights the importance of the highest power of 2 dividing $\varphi(n)$, which will feature prominently in the proof of Theorem 1 below.

What happens if we replace φ with a cognate arithmetic function? Candidates here include the sum of divisors function $\sigma(n)$ and Carmichael’s function $\lambda(n)$, defined as the exponent of the group $(\mathbf{Z}/n\mathbf{Z})^\times$. The estimates (1) and (2) remain valid with σ (see [2, pp. 31, 43] and [4, Theorem 2]), and it is straightforward to

prove that Theorem 1 also holds for σ . (See the remarks following the proof of the Theorem 3, which is a generalization of Theorem 1.) One can also show that (1) and (2) hold with φ replaced by λ (see [2, Theorem 6.3 and §7] and [3]). For sums of three squares, we can prove the following:

Theorem 2. *We have*

$$\begin{aligned} 0 &< \liminf_{x \rightarrow \infty} \frac{1}{x} \#\{n \leq x : \lambda(n) = \square + \square + \square\} \\ &\leq \limsup_{x \rightarrow \infty} \frac{1}{x} \#\{n \leq x : \lambda(n) = \square + \square + \square\} \\ &< 1. \end{aligned}$$

Perhaps surprisingly, we conjecture that Theorem 1 does *not* hold for λ . In fact, we believe that the liminf and limsup in Theorem 2 do not coincide, so that the set of n for which $\lambda(n) = \square + \square + \square$ does not possess an asymptotic density.

1.1. Notation

We write $\omega(n) := \sum_{p|n} 1$ for the number of distinct prime factors of n and $\Omega(n) := \sum_{p^e|n} 1$ for the number of prime factors of n counted with multiplicity. $P(n)$ denotes the largest prime factor of n , with the understanding that $P(1) = 1$. We write $d \parallel n$ (read “ d exactly divides n ”) if d divides n and $\gcd(d, n/d) = 1$. Throughout the paper, the letters p and q are reserved for primes. For each prime p and each natural number n , we write $v_p(n)$ for the p -adic order of n ; thus, $v_p(n) = 0$ if $p \nmid n$, and if $p \mid n$, then $v_p(n)$ is the unique positive integer for which $p^{v_p(n)} \parallel n$.

The Bachmann–Landau o and O -symbols (see [1, p. 401], [12, §12]), as well as Vinogradov’s \ll and \gg symbols, appear with their usual meanings. For $x > 0$, we set $\log_1 x = \max\{\log x, 1\}$, and we let \log_k denote the k th iterate of \log_1 .

2. Euler’s Function

2.1. Proof of Theorem 1

For each natural number m , define $u(m)$ (the *odd part* of m) by the relation $m = 2^{v_2(m)}u(m)$. Note that v_2 is completely additive while u is completely multiplicative.

Let G denote the group $(\mathbf{Z}/2\mathbf{Z}) \times (\mathbf{Z}/8\mathbf{Z})^\times$. We let θ denote the map from \mathbf{N} to G defined by

$$n \mapsto (v_2(\varphi(n)) \bmod 2, u(\varphi(n)) \bmod 8).$$

Then θ is a G -valued multiplicative function, in the sense that $\theta(mn) = \theta(m)\theta(n)$ whenever m and n are coprime. By Legendre’s theorem,

$$\varphi(n) = \square + \square + \square \iff \theta(n) \neq (0 \bmod 2, 7 \bmod 8).$$

To prove Theorem 1, we show that as n runs over the natural numbers, the elements $\theta(n) \in G$ become equidistributed.

Our starting point is a pretty theorem of Wirsing [24] from probabilistic number theory, which confirmed a conjecture of Erdős and Wintner.

Theorem A. *Let f be a real-valued multiplicative function satisfying $-1 \leq f(n) \leq 1$ for all $n \in \mathbf{N}$. If the series*

$$\sum_p \frac{1 - f(p)}{p}$$

diverges, then f has mean value zero.

Theorem A is enough to obtain Theorem 1 without the error term. To justify the error expression, we use the following effective version due to Hall and Tenenbaum [9] (see also [23, Theorem 7, p. 345]):

Theorem B. *Suppose that f is a real-valued multiplicative function with $-1 \leq f(n) \leq 1$ for all $n \in \mathbf{N}$. Let ϕ_0 be the unique solution on $(0, 2\pi)$ of the equation $\sin(\phi_0) + (\pi - \phi_0) \cos(\phi_0) = \frac{1}{2}\pi$, and put $L = \cos \phi_0 \approx 0.32867$. Then for $x \geq 1$,*

$$\frac{1}{x} \sum_{n \leq x} f(n) \ll \exp \left(-L \sum_{p \leq x} \frac{1 - f(p)}{p} \right),$$

where the implied constant is absolute.

Proof of Theorem 1. Let \hat{G} denote the character group of G . Since G has exponent 2, each $\chi \in \hat{G}$ assumes values in $\{1, -1\}$. Given $\chi \in \hat{G}$, we “lift” χ to \mathbf{N} by setting $\chi(n) = \chi(\theta(n))$ for each $n \in \mathbf{N}$. (By abuse of notation, we use the same symbol for the function on \mathbf{N} and the function on G .) Then χ is a multiplicative function taking values in $\{-1, 1\}$. By the orthogonality relations, to prove Theorem 1, it will suffice to show that

$$\sum_{n \leq x} \chi(n) \ll \frac{x}{(\log x)^{3/10}} \tag{4}$$

for each nontrivial χ .

We have $\hat{G} \cong (\widehat{\mathbf{Z}/2\mathbf{Z}}) \times (\widehat{\mathbf{Z}/8\mathbf{Z}})^\times$. Moreover, the isomorphism shows that for each nontrivial χ , there is a $\zeta \in \{-1, 1\}$ and a Dirichlet character $\tilde{\chi}$ to the modulus 8, with

$$\chi(n) = \zeta^{v_2(\varphi(n))} \tilde{\chi}(u(\varphi(n)))$$

for all natural numbers n . Since χ is nontrivial, either $\zeta \neq 1$ or $\tilde{\chi}$ is not the trivial character mod 8.

Suppose first that $\tilde{\chi}$ is trivial, so that $\zeta = -1$. In this case, $\chi(n) = (-1)^{v_2(\varphi(n))}$. Then $\chi(p) = -1$ whenever $p \equiv 3 \pmod{4}$, so that

$$\sum_{p \leq x} \frac{1 - \chi(p)}{p} \geq 2 \sum_{\substack{p \leq x \\ p \equiv 3 \pmod{4}}} \frac{1}{p} \sim \log \log x,$$

where the asymptotic relation holds as $x \rightarrow \infty$. Here we use a form of Dirichlet's theorem on primes in progressions (see, e.g., [5, p. 57]): Whenever a and m are coprime natural numbers,

$$\sum_{\substack{p \leq x \\ p \equiv a \pmod{m}}} \frac{1}{p} \sim \frac{1}{\varphi(m)} \log \log x \quad \text{as } x \rightarrow \infty. \tag{5}$$

The estimate (4) for this χ now follows from Theorem B. In fact, we can replace the exponent $3/10$ on the right-hand side of (4) with any constant smaller than L .

Suppose now that $\tilde{\chi}$ is nontrivial. Fix a large natural number K , and decompose

$$\begin{aligned} \sum_{p \leq x} \frac{\chi(p)}{p} &= \frac{\chi(2)}{2} + \sum_{1 \leq k \leq K} \zeta^k \sum_{\substack{b \pmod{8} \\ \gcd(b,8)=1}} \tilde{\chi}(b) \sum_{\substack{p \leq x \\ v_2(p-1)=k \\ u(p-1) \equiv b \pmod{8}}} \frac{1}{p} + \sum_{\substack{p \leq x \\ v_2(p-1) \geq K+1}} \frac{\chi(p)}{p} \\ &= \frac{\chi(2)}{2} + \sum_1 + \sum_2. \end{aligned}$$

We estimate the triple sum \sum_1 using (5): For fixed k and b , the condition on p in \sum_1 says precisely that $p \equiv 2^k b + 1 \pmod{2^{k+3}}$. So the sum over p is asymptotic (as $x \rightarrow \infty$) to $\frac{1}{2^{k+2}} \log \log x$. Notice that the coefficient of $\log \log x$ exhibits no dependence on b . Since $\sum \tilde{\chi}(b)$ vanishes when b runs over a system of coprime residues modulo 8, it follows that $\sum_1 = o(\log \log x)$ as $x \rightarrow \infty$. Also,

$$\limsup_{x \rightarrow \infty} \frac{1}{\log \log x} \left| \sum_2 \right| \leq \limsup_{x \rightarrow \infty} \frac{1}{\log \log x} \sum_{\substack{p \leq x \\ v_2(p-1) > K}} \frac{1}{p} = \frac{1}{2^K},$$

by (5) with $m = 2^{K+1}$ and $a = 1$. Since K was arbitrary, these estimates show that $\sum_{p \leq x} \chi(p)/p = o(\log \log x)$. But $\sum_{p \leq x} \frac{1}{p} \sim \log \log x$ (by (5) with $a = m = 1$), and so we deduce that

$$\sum_{p \leq x} \frac{1 - \chi(p)}{p} \sim \log \log x$$

as $x \rightarrow \infty$. Now (4) follows from Theorem B, as above. □

2.2. A Generalization

A similar argument allows us to prove a more general equidistribution result: Let \mathcal{Q} be a finite, nonempty set of primes, and redefine $u(n)$ as the part of n coprime to $\prod_{q \in \mathcal{Q}} q$, so that

$$n = u(n) \prod_{q \in \mathcal{Q}} q^{v_q(n)}.$$

Suppose that to each $q \in \mathcal{Q}$ is associated a positive integer m_q . Finally, assume that we are also given a positive integer l , and put

$$M := \prod_{q \in \mathcal{Q}} q^l. \tag{6}$$

We now introduce the group

$$G := \left(\prod_{q \in \mathcal{Q}} (\mathbf{Z}/m_q \mathbf{Z}) \right) \times (\mathbf{Z}/M \mathbf{Z})^\times,$$

and we define $\theta: \mathbf{N} \rightarrow G$ by

$$n \mapsto ((v_q(\varphi(n)) \bmod m_q)_{q \in \mathcal{Q}}, u(\varphi(n)) \bmod M).$$

Theorem 3. *As n ranges over \mathbf{N} , the elements $\theta(n)$ become equidistributed in G . In other words, for each $g \in G$, the set $\theta^{-1}(g)$ has asymptotic density $|G|^{-1} = (\varphi(M) \prod_{q \in \mathcal{Q}} m_q)^{-1}$.*

Remarks

1. We recover the density statement of Theorem 1 by taking $\mathcal{Q} = \{2\}$, $m_2 = 2$, and $l = 3$.
2. Since l may be taken arbitrarily large, it follows that the equidistribution statement of Theorem 3 holds for any M supported on the primes in \mathcal{Q} , not only those of the particular form (6).
3. The restriction to moduli M supported on primes in \mathcal{Q} is a natural one. Indeed, if M' is a fixed integer coprime to $\prod_{q \in \mathcal{Q}} q$, then $M' \mid u(\varphi(n))$ for almost all natural numbers n . A somewhat stronger claim appears as [14, Lemma 2].

The proof of Theorem 3 is similar to the argument of the last section. The key difference is that the characters of G need no longer be real-valued, so that Wirsing's theorem may not apply. But the following result of Hall [8] is a suitable stand-in:

Theorem C. *Let \mathcal{D} be a closed, convex proper subset of the closed unit disc in \mathbf{C} which contains 0. Suppose that f is a complex-valued multiplicative function satisfying $|f(n)| \leq 1$ for all $n \in \mathbf{N}$ and $f(p) \in \mathcal{D}$ for all primes p . If the series*

$$\sum_p \frac{1 - \Re(f(p))}{p} \tag{7}$$

diverges, then f has mean value zero. In fact, letting $L(\mathcal{D})$ denote the perimeter of \mathcal{D} , we have

$$\frac{1}{x} \left| \sum_{n \leq x} f(n) \right| \ll \exp \left(-\frac{1}{2} \left(1 - \frac{L(\mathcal{D})}{2\pi} \right) \sum_{p \leq x} \frac{1 - \Re(f(p))}{p} \right)$$

for $x \geq 1$. The implied constant here depends only on the region \mathcal{D} .

For each $\chi \in \hat{G}$, we lift χ to a multiplicative function on \mathbf{N} by setting $\chi(n) = \chi(\theta(n))$. We will apply Theorem C with $f = \chi$, where we take \mathcal{D} as the convex hull of the $\#G$ th roots of unity. Notice that for each prime p , either $f(p) = 1$ or $1 - \Re(f(p)) \geq 1 - \cos \frac{2\pi}{\#G} > 0$. (We assume here that $\#G > 1$; otherwise Theorem 3 is trivial.) So the series (7), with $f = \chi$, diverges if $\sum_{p: \chi(p) \neq 1} \frac{1}{p}$ diverges. We will show that this is true for every nontrivial χ .

Let χ be a nontrivial character. Then there are complex numbers $\{\zeta_q\}_{q \in \mathcal{Q}}$, with each $\zeta_q^{m_q} = 1$, and a Dirichlet character $\tilde{\chi} \pmod{M}$, with

$$\chi(n) = \left(\prod_{q \in \mathcal{Q}} \zeta_q^{v_q(\varphi(n))} \right) \tilde{\chi}(u(\varphi(n)))$$

for all $n \in \mathbf{N}$. Suppose first that $\tilde{\chi}$ is not trivial, and choose an integer a coprime to M with $\tilde{\chi}(a) \neq 1$. Then $\chi(p) = \tilde{\chi}(a) \neq 1$ for all primes p satisfying

$$p \equiv 1 + a \prod_{q \in \mathcal{Q}} q^{m_q} \pmod{\prod_{q \in \mathcal{Q}} q^{m_q+1}}.$$

The sum of the reciprocals of these primes p diverges by Dirichlet's theorem. Now suppose that $\tilde{\chi}$ is trivial. Since χ is nontrivial, we must have $\zeta_q \neq 1$ for some $q \in \mathcal{Q}$, say $\zeta_{q_0} \neq 1$. But then $\chi(p) = \zeta_{q_0} \neq 1$ if

$$p \equiv \begin{cases} 1 + q \pmod{q^2} & \text{when } q = q_0, \\ 1 + q^{m_q} \pmod{q^{m_q+1}} & \text{when } q \in \mathcal{Q} \setminus \{q_0\}. \end{cases}$$

The sum of the reciprocals of these primes diverges also, again by Dirichlet's result.

Remarks

1. As in Theorem 1, the error term in the asymptotic formula of Theorem 3 may be taken as $O(x/(\log x)^c)$ for some $c > 0$ (which may depend on \mathcal{Q} , the m_q , and l). To see this, we have only to insert into the above argument the form of Dirichlet’s result appearing in the proof of Theorem 1 and the quantitative half of Hall’s Theorem C.
2. To prove that Theorems 1 and 3 are valid with σ in place of φ , it is only necessary is to replace each (implicit) occurrence of “ $p - 1$ ” in the proofs with “ $p + 1$ ”. The reason this is so simple is that Theorems A–C refer only to the values of f at prime arguments, and not at proper prime powers.
3. It is clear that Theorem 3 does not hold for all positive integer-valued multiplicative functions, but a very general result of Ruzsa [19, Theorem (1.4)] implies that for any such function, each of the sets $\theta^{-1}(g)$ referred to in that theorem has an asymptotic density.

3. Carmichael’s Function

While Carmichael’s λ -function is not multiplicative, it is nonetheless easy to compute $\lambda(m)$ given the prime factorization of m . For any two coprime positive integers a and b , the isomorphism $(\mathbf{Z}/ab\mathbf{Z})^\times \cong (\mathbf{Z}/a\mathbf{Z})^\times \times (\mathbf{Z}/b\mathbf{Z})^\times$ yields that $\lambda(ab) = \text{lcm}[\lambda(a), \lambda(b)]$. As a consequence,

$$\lambda(m) = \text{lcm}\{\lambda(p^k) : p^k \parallel m\}; \tag{8}$$

moreover, for each prime power p^k ,

$$\lambda(p^k) = \begin{cases} p^{k-1}(p-1) & \text{if } p \text{ is odd, or if } p = 2 \text{ but } k \in \{1, 2\}, \\ p^{k-2} & \text{if } p = 2 \text{ and } k \geq 3. \end{cases} \tag{9}$$

(For a proof of (9), see, e.g., [10, Chapter 4].) These facts will be used without further comment in the sequel.

We will treat the upper and lower bounds in Theorem 2 separately. To begin, we need a strengthening of (5) in the case $a = 1$, which can be found in [16] or [18]:

Lemma 4. *For all integers $m > 1$ and all $x \geq 3$,*

$$\sum_{\substack{p \leq x \\ p \equiv 1 \pmod{m}}} \frac{1}{p} = \frac{\log \log x}{\varphi(m)} + O\left(\frac{\log m}{\varphi(m)}\right), \tag{10}$$

with an O -constant uniform in both m and x .

The next lemma is implicit in the work of Li [13, proof of Theorem 3.1]. We include a proof for the sake of completeness.

Lemma 5. *Fix $H > 0$. Suppose that x is large, depending on H . Then for any integer R with $\frac{\log_3 x}{\log 2} - H \leq R \leq \frac{\log_3 x}{\log 2} + H$, there are $\gg x$ values of $n \leq x$ satisfying $v_2(\lambda(n)) = R$. The implied constant here depends at most on H .*

Proof. We will construct $\gg x$ odd numbers $n \leq x$ of the form mp , where $v_2(p-1) = R$ and

$$v_2(q-1) < R \quad \text{for all primes } q \mid m. \tag{11}$$

Notice that each n constructed in this way satisfies $v_2(\lambda(n)) = \max_{p \mid n} v_2(p-1) = R$, as desired.

Fix a prime $p \leq x^{1/2}$ satisfying $v_2(p-1) = R$. For each such p , we count the number of odd $m \leq x/p$ satisfying (11). Put $y := \exp(\log x / \log \log x)$, and from all odd $m \leq x/p$, remove those with a prime factor $q \equiv 1 \pmod{2^R}$ with $q \leq y$. Since $y = x^{o(1)}$ and $x/p \geq x^{1/2}$, the fundamental lemma of the sieve (see [7, Theorem 7.2]) guarantees that the number of m surviving this process is

$$\gg \frac{x}{2p} \prod_{\substack{q \leq y \\ q \equiv 1 \pmod{2^R}}} \left(1 - \frac{1}{q}\right) \gg \frac{x}{p} \exp\left(- \sum_{\substack{q \leq y \\ q \equiv 1 \pmod{2^R}}} \frac{1}{q}\right).$$

We estimate the sum over q with (10). Since $2^R \asymp \log \log x$, we see that

$$\sum_{\substack{q \leq y \\ q \equiv 1 \pmod{2^R}}} \frac{1}{q} = \frac{\log \log y}{\varphi(2^R)} + O\left(\frac{\log(2^R)}{2^R}\right) \ll 1,$$

and so the number of remaining m is $\gg x/p$. If m has not been sieved out, but m fails (11), then m has a prime divisor $q \equiv 1 \pmod{2^R}$ with $q > y$. But the number of such m is

$$\ll \frac{x}{p} \sum_{\substack{y < q \leq x/p \\ q \equiv 1 \pmod{2^R}}} \frac{1}{q} = \frac{x}{p} \left(\frac{\log \log(x/p) - \log \log y}{\varphi(2^R)} + O\left(\frac{\log(2^R)}{2^R}\right) \right) \ll \frac{x \log \log \log x}{p \log \log x}.$$

So for large x , the number of odd $m \leq x/p$ satisfying (11) is $\gg x/p$, uniformly in p . Summing over p , we see that the number of n constructed in this way is

$$\begin{aligned} &\gg x \sum_{\substack{p \leq x^{1/2} \\ p \equiv 1 \pmod{2^R} \\ p \not\equiv 1 \pmod{2^{R+1}}}} \frac{1}{p} = x \left(\frac{\log \log(x^{1/2})}{\varphi(2^R)} - \frac{\log \log(x^{1/2})}{\varphi(2^{R+1})} \right) + O\left(x \frac{\log(2^R)}{2^R}\right) \\ &= x \frac{\log \log x}{2^R} + O\left(x \frac{\log \log \log x}{\log \log x}\right) \gg x. \end{aligned}$$

Notice that there is no overcounting here, since in the decomposition $n = mp$, the prime p is the unique prime divisor of n with $v_2(p - 1) = R$. \square

We can now prove half of Theorem 2.

Proof of the lower bound in Theorem 2. Applying Lemma 5 with $H = 1$ and R the nearest odd integer to $\log_3 x / \log 2$ (breaking ties arbitrarily), we see that there are $\gg x$ values of $n \leq x$ with $v_2(\lambda(n))$ odd. But then $\lambda(n) = \square + \square + \square$ by Legendre’s criterion. \square

The proof of the upper bound in Theorem 2 is more difficult. The strategy we will use was suggested to the author by Florian Luca and Carl Pomerance.

We begin by quoting a special case of [6, Theorem 4.1]. Let

$$E(n, x) := \sum_{\substack{p \leq \log \log x \\ p \nmid \lambda(n)}} \frac{1}{p} + \sum_{\substack{p > \log \log x \\ p \mid \lambda(n)}} \frac{1}{p}. \tag{12}$$

Lemma 6. *For $x \geq 1$, we have $\sum_{n \leq x} E(n, x) \ll x / \log_3 x$.*

In [6], the lemma is stated with $\varphi(n)$ in place of $\lambda(n)$, but from (8) and (9), the numbers $\varphi(n)$ and $\lambda(n)$ always share the same set of prime factors. As an immediate consequence of Lemma 6, the number of $n \leq x$ with $E(n, x) > \epsilon$ is $\ll \epsilon^{-1} x / \log_3 x$.

Proof of the upper bound in Theorem 2. We start with a summary of our strategy: Let R be the nearest even integer to $\frac{\log_3 x}{\log 2}$, and consider pairs (m, p) with $v_2(\lambda(m)) = R$ and $v_2(p - 1) \leq R$. Assume also that p is coprime to m . Then with $n := mp$,

$$\lambda(n) = \frac{p - 1}{d} \lambda(m), \quad \text{where } d := \gcd(p - 1, \lambda(m)).$$

The number $(p - 1)/d$ is odd, so that $v_2(\lambda(n)) = v_2(\lambda(m)) = R$. In particular, $v_2(\lambda(n))$ is even. Using again $u(\cdot)$ to denote the odd part, we have that

$$u(\lambda(n)) = \frac{p - 1}{d} u(\lambda(m)).$$

Thus, if we define $A_m \in \{1, 3, 5, 7\}$ so that

$$A_m \cdot u(\lambda(m)) \equiv 7 \pmod{8},$$

and if p is such that

$$\frac{p - 1}{d} \equiv A_m \pmod{8}, \tag{13}$$

then $u(\lambda(n)) \equiv 7 \pmod{8}$. So by Legendre’s criterion, $\lambda(n)$ is not a sum of three squares. We now show how to construct $\gg x$ such values of $n \leq x$.

Since we are seeking a lower bound, we are free to impose convenient conditions on the pairs (m, p) which we consider. In order to ensure that p is coprime to m and that the representation of n in the form mp is unique (so as to avoid overcounting), we require that

$$x^{1/6} < m \leq x^{1/3}$$

and that

$$\frac{1}{2}x/m < p \leq x/m,$$

so that $p > \frac{1}{2}x^{2/3} > x^{1/3} \geq m$ for large x . Thus, the number of $n \leq x$ for which $\lambda(n) \neq \square + \square + \square$ is bounded below by

$$\sum_d \sum_{\substack{x^{1/6} < m \leq x^{1/3} \\ d|\lambda(m) \\ v_2(\lambda(m))=R}} \sum_{\substack{\frac{1}{2}x/m < p \leq x/m \\ (p-1, \lambda(m))=d \\ v_2(p-1) \leq R \\ \frac{p-1}{d} \equiv A_m \pmod{8}}} 1.$$

To simplify the situation slightly, let us sum only over d for which $2 \parallel d$. Note that for large x , the condition $v_2(p - 1) \leq R$ then follows automatically from the two conditions $(p - 1, \lambda(m)) = d$ and $v_2(\lambda(m)) = R$; in fact, we get that $v_2(p - 1) = 1$. For technical reasons having to do with limitations in the range of uniformity of the prime number theorem in arithmetic progressions, we impose further arithmetic restrictions on m and d : We require that $E(m, x)$, defined by (12), satisfies

$$E(m, x) \leq 1$$

and that the number and size of the prime factors of d are constrained,

$$\Omega(d) \leq 2 \log_4 x \quad \text{and} \quad P(d) \leq \log \log x. \tag{14}$$

Reordering the sums, we are led to the following lower bound, valid for all large x :

$$\#\{n \leq x : \lambda(n) \neq \square + \square + \square\} \geq \sum_{\substack{x^{1/6} < m \leq x^{1/3} \\ v_2(\lambda(m))=R \\ E(m,x) \leq 1}} \sum_{\substack{d|\lambda(m), 2 \parallel d \\ P(d) \leq \log \log x \\ \Omega(d) \leq 2 \log_4 x}} \sum_{\substack{\frac{1}{2}x/m < p \leq x/m \\ \frac{p-1}{d} \equiv A_m \pmod{8} \\ (p-1, \lambda(m))=d}} 1. \tag{15}$$

Instead of requiring in the final sum of (15) that $\gcd(p - 1, \lambda(m)) = d$, for the sake of subsequent estimates it is expedient to impose a slightly weaker condition on p , viz.

$$\min\{v_q(p - 1), v_q(\lambda(m))\} = v_q(d) \quad \text{for all } q \leq \log_2 x. \tag{16}$$

In other words, we require only that d be the $(\log_2 x)$ -smooth part of $\gcd(p - 1, \lambda(m))$. This change causes us to count some additional integers, but this does not hurt us since, as we show below, the number $A(x)$ of additional integers satisfies

$$A(x) \ll x / \log_3 x. \tag{17}$$

Indeed, suppose that p satisfies (16) but that $\gcd(p - 1, \lambda(m)) \neq d$. Since $P(d) \leq \log_2 x$, it follows that there is some $q > \log_2 x$ with $q \mid \gcd(p - 1, \lambda(m))$. So the contribution of these p to the right-hand side of (15) is bounded by

$$\begin{aligned} \sum_{x^{1/6} < m \leq x^{1/3}} \sum_{\substack{q > \log \log x \\ q \mid \lambda(m)}} \sum_{\substack{p \leq x/m \\ q \mid p-1}} 1 &\ll \sum_{x^{1/6} < m \leq x^{1/3}} \sum_{\substack{q > \log \log x \\ q \mid \lambda(m)}} \frac{x}{mq \log x} \\ &\ll \frac{x}{\log x} \sum_{x^{1/6} < m \leq x^{1/3}} \frac{1}{m} \sum_{\substack{q > \log \log x \\ q \mid \lambda(m)}} \frac{1}{q}. \end{aligned}$$

(Here we have applied the Brun–Titchmarsh inequality; note that $mq \leq m^2 \leq x^{2/3}$, so that $\log \frac{x}{mq} \gg \log x$.) For $x^{1/6} \leq y \leq x^{1/3}$, we have

$$\sum_{m \leq y} \sum_{\substack{q > \log \log x \\ q \mid \lambda(m)}} \frac{1}{q} \leq \sum_{m \leq y} E(m, y) \ll \frac{y}{\log_3 y},$$

so that by Abel summation,

$$\sum_{x^{1/6} < m \leq x^{1/3}} \frac{1}{m} \sum_{\substack{q > \log \log x \\ q \mid \lambda(m)}} \frac{1}{q} \ll \frac{\log x}{\log_3 x}.$$

Collecting our estimates, we have (17). Hence, to show that the right-hand side of (15) is $\gg x$, it is enough to show that

$$\sum_m \sum_d \sum_{\substack{x/2m < p \leq x/m \\ p \text{ satisfies (13), (16)}}} 1 \gg x. \tag{18}$$

Here and below, a sum over m or d without additional subscripts indicates that the conditions of summation are the same as in (15).

The sum over p in (18) can be estimated using standard results on the distribution of primes in progressions. We may interpret (13) and (16) as asserting that p falls into a certain collection of residue classes modulo M , where

$$M := 8d \prod_{\substack{2 < q \leq \log \log x \\ q \mid \lambda(m)/d}} q.$$

Notice that by the prime number theorem and (14),

$$M \leq 8d \prod_{q \leq \log \log x} q \leq 8(\log \log x)^{2 \log_4 x} (\log x)^{1+o(1)} < (\log x)^{3/2}$$

for large x . One checks that the number of coprime residue classes modulo M consistent with both (13) and (16) is

$$\frac{\varphi(M)}{8} \frac{1}{\varphi(d/2)} \prod_{\substack{q|\lambda(m)/d \\ 2 < q \leq \log \log x}} \left(1 - \frac{1}{q}\right).$$

Now a moderately strong form of the prime number theorem for progressions (see, e.g., [5, Chapter 20]) gives that the sum over p in (18) is

$$\begin{aligned} &\gg \left(\frac{1}{\varphi(d)} \prod_{\substack{q|\lambda(m)/d \\ q \leq \log \log x}} \left(1 - \frac{1}{q}\right) \right) \frac{x}{m \log x} \geq \frac{1}{\varphi(d)} \frac{x}{m \log x} \prod_{q \leq \log \log x} \left(1 - \frac{1}{q}\right) \\ &\gg \frac{1}{\varphi(d)} \frac{x}{m \log x} \frac{1}{\log \log \log x}. \end{aligned}$$

Hence the triple sum on the left-hand side of (18) is

$$\gg \frac{x}{\log x} \sum_m \frac{1}{m} \left(\frac{1}{\log \log \log x} \sum_d \frac{1}{\varphi(d)} \right). \tag{19}$$

We now turn our attention to the sum over d in (19). We start by observing that

$$\sum_d \frac{1}{\varphi(d)} \geq \sum_{\substack{d|\lambda(m), 2\|d \\ P(d) \leq \log \log x}} \frac{1}{\varphi(d)} - \sum_{\substack{d|\lambda(m), 2\|d \\ P(d) \leq \log \log x \\ \Omega(d) > 2 \log_4 x}} \frac{1}{\varphi(d)}. \tag{20}$$

The first right-hand sum in (20) is easy to estimate: Since $\lambda(m)$ is even, we have

$$\begin{aligned} \sum_{\substack{d|\lambda(m), 2\|d \\ P(d) \leq \log \log x}} \frac{1}{\varphi(d)} &\geq \sum_{\substack{d|\lambda(m), 2\|d \\ P(d) \leq \log \log x \\ d \text{ squarefree}}} \frac{1}{\varphi(d)} = \frac{1}{\varphi(2)} \prod_{\substack{2 < q \leq \log \log x \\ q|\lambda(m)}} \left(1 + \frac{1}{q-1}\right) \\ &\gg \exp \left(\sum_{\substack{q|\lambda(m) \\ q \leq \log \log x}} \frac{1}{q} \right) \gg \log \log \log x, \end{aligned}$$

where we use that

$$\sum_{\substack{q|\lambda(m) \\ q \leq \log \log x}} \frac{1}{q} \geq \sum_{q \leq \log \log x} \frac{1}{q} - E(m, x) \geq \log_4 x + O(1).$$

(Recall that $E(m, x) \leq 1$.) We now show that the second sum on the right-hand side of (20) is $o(\log_3 x)$, so that the left-hand side of (20) is $\gg \log_3 x$. Consider first

the contribution of those d with $\omega(d) > \frac{3}{2} \log_4 x$. Using the multinomial theorem, we see that this contribution is bounded by

$$\begin{aligned} \sum_{\substack{d: P(d) \leq \log \log x \\ \omega(d) > \frac{3}{2} \log_4 x}} \frac{1}{\varphi(d)} &\leq \sum_{k > \frac{3}{2} \log_4 x} \frac{1}{k!} \left(\sum_{q \leq \log_2 x} \left(\frac{1}{\varphi(q)} + \frac{1}{\varphi(q^2)} + \dots \right) \right)^k \\ &\leq \sum_{k > \frac{3}{2} \log_4 x} \frac{1}{k!} (\log_4 x + O(1))^k < (\log_3 x)^{9/10}. \end{aligned}$$

(To verify the last estimate in this chain, it is helpful to keep in mind the elementary inequality $k! \geq (k/e)^k$ and to observe that the sum over k is dominated by its first term.) Now consider the contribution of those d with $\omega(d) \leq \frac{3}{2} \log_4 x$. Write $d = d_1 d_2$, where d_1 is the largest squarefree divisor of d . Then

$$\Omega(d_2) = \Omega(d) - \Omega(d_1) = \Omega(d) - \omega(d) > \frac{1}{2} \log_4 x.$$

Put $e := d_2 \prod_{q|d_2} q$. Then e is a squarefull divisor of d , and clearly

$$e \geq 2^{\Omega(e)} \geq 2^{\Omega(d_2)} > 2^{\frac{1}{2} \log_4 x}.$$

Moreover, e is coprime to $d' := d/e$, and so $\varphi(d) = \varphi(e)\varphi(d')$. So the contribution from these d to the second sum on the right of (20) is

$$\begin{aligned} \ll \sum_{\substack{e \text{ squarefull} \\ e > 2^{(\log_4 x)/2}}} \frac{1}{\varphi(e)} \sum_{\substack{d'|\lambda(m) \\ P(d') \leq \log_2 x \\ d' \text{ squarefree}}} \frac{1}{\varphi(d')} &\leq \sum_{\substack{e \text{ squarefull} \\ e > 2^{(\log_4 x)/2}}} \frac{1}{\varphi(e)} \prod_{q \leq \log_2 x} \left(1 + \frac{1}{q-1} \right) \\ &\ll \log_3 x \sum_{\substack{e \text{ squarefull} \\ e > 2^{(\log_4 x)/2}}} \frac{1}{\varphi(e)}. \end{aligned}$$

The final sum over e is the tail of a convergent series, since

$$\sum_{e \text{ squarefull}} \frac{1}{\varphi(e)} = \prod_q \left(1 + \frac{1}{\varphi(q^2)} + \frac{1}{\varphi(q^3)} + \dots \right) < \infty.$$

So those d with $\omega(d) \leq \frac{3}{2} \log_4 x$ also contribute $o(\log_3 x)$, as desired.

Referring back to (19), we now have a lower bound which is

$$\gg \frac{x}{\log x} \sum_{\substack{x^{1/6} < m \leq x^{1/3} \\ v_2(\lambda(m))=R \\ E(m,x) \leq 1}} \frac{1}{m}.$$

For $x^{1/6} \leq y \leq x^{1/3}$, there are $\gg y$ values of $m \leq y$ with $v_2(\lambda(m)) = R$, by Lemma 5. (We use here that \log_3 is very slowly varying, so that $|\frac{\log_3 y}{\log 2} - R| \leq 1.1$, say, for all such y .) Requiring $E(m, x) \leq 1$ excludes only $o(y)$ of these m . (Indeed, if $E(m, x) > 1$, then $E(m, y) \geq 1/2$, and there are only $o(y)$ of these m in $[1, y]$ by Lemma 6.) The estimate $\sum \frac{1}{m} \gg \log x$ now follows by partial summation. Inserting this above shows that there are $\gg x$ values of $n \leq x$ for which $\lambda(n)$ is not a sum of three squares. \square

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