COUNTING ELLIPTIC CURVES WITH AN ISOGENY OF DEGREE THREE

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Abstract. We count by height the number of elliptic curves over $\mathbb{Q}$ that possess an isogeny of degree 3.

1. Introduction

Torsion subgroups of elliptic curves have long been an object of fascination for mathematicians. By work of Duke [1], elliptic curves over $\mathbb{Q}$ with nontrivial torsion are comparatively rare. Recently, Harron–Snowden [3] have refined this result by counting elliptic curves over $\mathbb{Q}$ with prescribed torsion, as follows. Every elliptic curve $E$ over $\mathbb{Q}$ is defined uniquely up to isomorphism by an equation of the form
\begin{equation}
E: y^2 = f(x) = x^3 + Ax + B
\end{equation}
with $A, B \in \mathbb{Z}$ such that $4A^3 + 27B^2 \neq 0$ and there is no prime $\ell$ such that $\ell^4 \mid A$ and $\ell^6 \mid B$. We define the height of such $E$ by
\begin{equation}
\text{ht}(E) := \max(|4A^3|, |27B^2|).
\end{equation}

For a possible torsion subgroup (allowed by Mazur’s theorem [5]), Harron–Snowden [3, Theorem 1.5] prove that
\[
\#\{E : \text{ht}(E) \leq X \text{ and } E(\mathbb{Q})_{\text{tors}} \simeq G\} \asymp X^{1/d(G)}
\]
where $d(G) \in \mathbb{Q}$ is explicitly given, and $f(X) \asymp g(X)$ means that there exist positive constants $c_1, c_2$ such that $c_1 g(X) \leq f(X) \leq c_2 g(X)$. In the case $G \simeq \mathbb{Z}/2\mathbb{Z}$, i.e., the case of 2-torsion, they show the count is $cX^{1/2} + O(X^{1/3})$ for an explicit constant $c \approx 3.1969$ [3, Theorem 5.5]. (For weaker but related results, see also Duke [1, Proof of Theorem 1] and Grant [2, Section 2].)

In this article, we count elliptic curves with a nontrivial cyclic isogeny defined over $\mathbb{Q}$. An elliptic curve has a 2-isogeny if and only if it has a 2-torsion point, so the above result of Duke, Grant, and Harron–Snowden handles this case. The next interesting case concerns isogenies of degree 3. Our main result is as follows.

**Theorem 1.3.** Let $N_3(X)$ count the number of elliptic curves $E$ with $\text{ht}(E) \leq X$ that possess a 3-isogeny defined over $\mathbb{Q}$. Then there exist constants $c_1, c_2$ such that
\[
N_3(X) = \frac{2}{3\sqrt{3}\zeta(6)}X^{1/2} + c_1X^{1/3}\log X + c_2X^{1/3} + O(X^{7/24}).
\]
Moreover, we have
\[
c_1 = \frac{c_0}{8\pi^2\zeta(4)} = 0.107437 \ldots
\]
where $c_0$ is an explicitly given integral (4.8), and the constant $c_2$ is effectively computable.
We obtain the same asymptotic in Theorem 1.3 if we instead count elliptic curves equipped with a 3-isogeny (that is, counting with multiplicity): see Proposition 2.10. Surprisingly, the main term of order $X^{1/2}$ counts just those elliptic curves with $A = 0$ and $j$-invariant equal to 0 (having complex multiplication by the quadratic order of discriminant $-3$). Theorem 1.3 matches computations performed out to $X = 10^{25}$—see section 6.

The difficulty in computing the constant $c_2$ in the above theorem arises in applying a knotty batch of local conditions; our computations suggest that $c_2 \approx 0.16$. If we count without these conditions, we find the explicit constant $c_6 = 1.1204\ldots$, given in (5.4)—it is already quite complicated.

Theorem 1.3 may be interpreted in alternative geometric language as follows. Let $X_0(3)$ be the modular curve parametrizing (generalized) elliptic curves equipped with an isogeny of degree 3. Then $N(X)$ counts rational points of bounded height on $X_0(3)$ with respect to the height arising from the pullback of the natural height on the $j$-line $X(1)$. From this vantage point, the main term corresponds to a single elliptic point of order 3 on $X_0(3)$! The modular curves $X_0(N)$ are not fine moduli spaces (owing to quadratic twists), so our proof of Theorem 1.3 is quite different than the method used by Harron–Snowden: in particular, a logarithmic term presents itself for the first time. We hope that our method and the lower-order terms in our result will be useful in understanding counts of rational points on stacky curves more generally.

**Contents.** The paper is organized as follows. We begin in section 2 with a setup and exhibiting the main term, then in section 3 as a warmup we prove the right order of magnitude for the secondary term. In section 4, we refine this approach to prove an asymptotic for the secondary term, and then we exhibit a tertiary term in section 5. We conclude in section 6 with our computations.

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2. Setup

In this section, we set up the problem in a manner suitable for direct investigation. We continue the notation from the introduction.

Let $\mathcal{E}$ denote the set of elliptic curves $E$ over $\mathbb{Q}$ in the form (1.1) (minimal, with nonzero discriminant). For $X \in \mathbb{R}_{>0}$, let $\mathcal{E}_{\leq X} := \{E \in \mathcal{E} : \text{ht}(E) \leq X\}$ be the set of elliptic curves $E$ over $\mathbb{Q}$ with height at most $X$. We are interested in asymptotics for the functions

$$N_3(X) := \# \{E \in \mathcal{E}_{\leq X} : E \text{ has a 3-isogeny defined over } \mathbb{Q}\},$$

$$N'_3(X) := \# \{(E, \phi) : E \in \mathcal{E}_{\leq X} \text{ and } \phi : E \to E' \text{ is a 3-isogeny defined over } \mathbb{Q}\}.$$  

To that end, let $E = E_{A,B} \in \mathcal{E}$, with $A, B \in \mathbb{Z}$. The 3-division polynomial of $E$ [7, Exercise 3.7] is equal to

$$\psi(x) = \psi_{A,B}(x) := 3x^4 + 6Ax^2 + 12Bx - A^2;$$

the roots of $\psi(x)$ are the $x$-coordinates of nontrivial 3-torsion points on $E$.

**Lemma 2.3.** The elliptic curve $E$ has a 3-isogeny defined over $\mathbb{Q}$ if and only if $\psi(x)$ has a root $a \in \mathbb{Q}$.
Proof. Let $\varphi: E \to E'$ be a 3-isogeny defined over $\mathbb{Q}$. Then $\ker \varphi = \{\infty, \pm P\}$ is stable under the absolute Galois group $\text{Gal}_\mathbb{Q}$, so $\sigma(P) = \pm P$. Thus, $\sigma(x(P)) = x(P)$ for all $\sigma \in \text{Gal}_\mathbb{Q}$ and hence $a = x(P) \in \mathbb{Q}$ is a root of $\psi(x)$ by definition. Conversely, if $\psi(a) = 0$ with $a \in \mathbb{Q}$, then letting $\pm P := (a, \pm \sqrt{f(a)})$ we obtain $C := \{\infty, \pm P\}$ a Galois stable subgroup of order 3 and accordingly the map $\varphi: E \to E/C = E'$ is a 3-isogeny defined over $\mathbb{Q}$: explicitly, by the formula of Vélu we have

$$E': y^2 = x^3 - 16(9A + 30a^2)x - (9A^2/a + 114Aa + 253a^3)$$

(but such $E'$ is not necessarily in our designated form). \qed

**Lemma 2.4.** If $a \in \mathbb{Q}$ is a root of $\psi(x)$, then $a \in \mathbb{Z}$.

Proof. For the first statement, by the rational root test, $a_0 = 3a \in \mathbb{Z}$. Thus

$$0 = 27\psi(a) = a_0^4 + 18Aa_0^2 + 108Ba_0 - 27A^2$$

so $3 \mid a_0$, whence $a \in \mathbb{Z}$. \qed

Although the polynomial $\psi(x)$ is irreducible in $\mathbb{Z}[A, B][x]$, the special case where $A = 0$ gives $\psi_{0,B}(x) = 3x(x^3 + 4B)$ and so $a = 0$ is automatically a root, corresponding to the elliptic curve $E: y^2 = x^3 + B$ and the isogeny $\varphi: E \to E'$ by

$$\varphi(x, y) = \left(\frac{x^3 + 4B}{x^2}, \frac{x^3 - 8B}{x^3}y\right)$$

We count these easily.

**Lemma 2.7.** Let $N_3(X)_{A=0}$ be defined as in (2.1) but restricted to $E \in \mathcal{E}_{\leq X}$ with $A = 0$. Then

$$N_3(X)_{A=0} = \frac{2}{3\sqrt{3}\zeta(6)}X^{1/2} + O(X^{1/6}) \quad \text{and} \quad N'_3(X)_{A=0} = N_3(X)_{A=0} + O(X^{1/6}).$$

Proof. In light of the above, we have

$$N_3(X)_{A=0} = \#\{B \in \mathbb{Z} : |27B^2| \leq X \text{ and } \ell^6 \nmid B \text{ for any prime } \ell\};$$

a standard sieve gives this count as $\frac{2}{3\sqrt{3}\zeta(6)}X^{1/2} + O(X^{1/12})$, see Pappalardi [6]. If such an elliptic curve had another 3-isogeny, corresponding to a root of $\psi(x)/x = x^3 + 4B$, then $-4B$ is a cube and the count of such is $O(X^{1/6})$. \qed

With these lemmas in hand, we define our explicit counting function. For $X > 0$, let $N(X)$ denote the number of ordered triples $(A, B, a) \in \mathbb{Z}^3$ satisfying:

(N1) $A \neq 0$ and $\psi_{A,B}(a) = 0$;
(N2) $|4A^3| \leq X$ and $|27B^2| \leq X$;
(N3) $4A^3 + 27B^2 \neq 0$; and
(N4) there is no prime $\ell$ with $\ell^4 \mid A$ and $\ell^6 \mid B$.

That is to say, we define

$$(2.8) \quad N(X) := \#\{(A, B, a) \in \mathbb{Z}^3 : \text{all conditions (N1)–(N4) hold}\}.$$

We have excluded from $N(X)$ the count for $A = 0$ from the function $N(X)$; we have handled this in Lemma 2.7.
Corollary 2.9. We have
\[ N'_3(X) = \frac{2}{3 \sqrt{3} \zeta(6)} X^{1/2} + N(X) + O(X^{1/6}). \]

Proof. This corollary is immediate from Lemmas 2.3, 2.4, and 2.7. □

To conclude this section, we compare \( N_3(X) \) and \( N'_3(X) \).

Proposition 2.10. We have
\[ N'_3(X) = N_3(X) + O(X^{1/6} \log X) \]

Proof. The difference \( N'_3(X) - N_3(X) \) counts elliptic curves with more than one 3-isogeny. Let \( E \) be an elliptic curve with (at least) two 3-isogenies \( \varphi_i : E \to E'_i \) and let \( \ker \varphi_i = \langle P_i \rangle \) for \( i = 1, 2 \). Then \( \langle P_1, P_2 \rangle = E[3] \), and so the image of \( \text{Gal}_{\mathbb{Q}} \) acting on \( E[3] \) is a subgroup of the group of diagonal matrices in \( \text{GL}_2(\mathbb{F}_3) \). This property is preserved by any twist of \( E \), so such elliptic curves are characterized by the form of their \( j \)-invariant, explicitly [8, Table 1, 3D-3a]

\[ j(t) = \left( \frac{(t(t+6)(t^2-6t+36)}{(t-3)(t^2+3t+9)} \right)^3 \]

for \( t \in \mathbb{Q} \setminus \{ 3 \} \). Computing an elliptic surface for this \( j \)-invariant, we conclude that every such \( E \) is of the form \( y^2 = x^3 + u^2 A(t)x + u^3 B(t) \) for some \( t, u \in \mathbb{Q} \), where

\[ A(t) = -3t(t+6)(t^2-6t+36) = -3t^4 - 648t, \]
\[ B(t) = 2(t^2-6t-18)(t^4+6t^3+54t^2-108t+324) = 2t^6 - 1080t^3 - 11664. \]

Then by Harron–Snowden [3, Proposition 4.1] (with \( (r,s) = (4,6) \) so \( m = 1 \) and \( n = 2 \)), the number of such elliptic curves is bounded above (and below) by a constant times \( X^{1/6} \log X \), as claimed. □

In light of the above, our main result will follow from an asymptotic for the easier function \( N(X) \) defined in (2.8), and so we proceed to study this function.

3. Order of magnitude

In this section, we introduce new variables \( u, v, w \) that will be useful in the sequel, and provide an argument that shows the right order of magnitude. This argument explains the provenance of the logarithmic term in a natural way and motivates our approach. We recall (2.8), the definition of \( N(X) \).

Theorem 3.1. There exist \( c_3, c_4, X_0 \in \mathbb{R}_{>0} \) such that for all \( X \geq X_0 \), we have
\[ c_3 X^{1/3} \log X \leq N(X) \leq c_4 X^{1/3} \log X. \]

We begin with a few observations. First, if \( A, B, a \in \mathbb{Z} \) and \( \psi_{A,B}(a) = 0 \), then
\[ 12B = \frac{A^2}{a} - 6Aa - 3a^3. \]

Lemma 3.3. Let \( A, a \in \mathbb{Z} \) with \( a \neq 0 \). Then \( (A^2/a) - 6Aa - 3a^3 \in 12\mathbb{Z} \) if and only if all of the following conditions hold:

(B1) \( a \mid A^2 \) and \( 3 \mid (A^2/a) \);
(B2) $A, a$ have the same parity; and
(B3) If $A, a$ are both even, then $4 \mid (A^2/a)$.

Proof. The verification is straightforward. \hfill \square

Lemma 3.4. Let $A, B, a \in \mathbb{Z}$ satisfy conditions (N1)–(N2). Then
\begin{equation}
|a| \ll X^{1/6} \quad \text{and} \quad A^2/|a| \ll X^{1/2}.
\end{equation}

Proof. Let $\alpha := a/X^{1/6}$. Since $|A| < 4^{-1/3}X^{1/3}$, we have
\[A^2/|a| < 4^{-2/3}|\alpha|^{-1}X^{1/2}, \quad |Aa| < 4^{-1/3}|\alpha|X^{1/2}.
\]
The inequality for $B$ and (3.2) imply that there exist $A, B, a \in \mathbb{Z}$ such that
\begin{equation}
A^2/|a| < 12|B| + 6|Aa| + 3|\alpha|^3,
\end{equation}
so that
\begin{equation}
3|\alpha|^3 \leq \frac{4}{3^{1/2}} X^{1/2} + 6|Aa| + A^2/|a|,
\end{equation}

The inequality (3.6) fails for $|\alpha|$ large—in fact, we have $|\alpha| < 11/8$—which proves the first part of (3.5). To get the second part, note that the first part and condition (N2) imply that $|Aa| \ll X^{1/2}$. And since (3.2) implies that
\[A^2/|a| \leq 12|B| + 6|Aa| + 3|\alpha|^3,
\]
we have $A^2/|a| \ll X^{1/2}$. \hfill \square

Proof of Theorem 3.1. We first prove the upper bound. Every nonzero $a \in \mathbb{Z}$ can be written uniquely as $a = uv^2$, where $u \in \mathbb{Z}$ is squarefree and $v \in \mathbb{Z}_{>0}$. Replacing $a = uv^2$, we see that $a \mid A^2$ if and only if $uv \mid A$. Therefore $A = uvw$ with $w \in \mathbb{Z}$ arbitrary. The inequalities in (3.5) imply that there exist $c_5, c_6 > 0$ such that
\begin{equation}
0 < |u|v^2 \leq c_5 X^{1/6} \quad \text{and} \quad 0 < |u|w^2 \leq c_6 X^{1/2}.
\end{equation}
Thus,
\begin{equation}
N(X) \leq \# \{(u, v, w) \in \mathbb{Z}^3 : u \text{ squarefree}, v > 0, \text{ and the inequalities (3.7) hold}\}.
\end{equation}

For $X \geq 2$, we have
\begin{align}
N(X) & \leq \sum_{|u|v^2 \leq c_5 X^{1/6}} \sum_{|u|w^2 \leq c_6 X^{1/2}} 1 \ll \sum_{|u|v^2 \leq c_5 X^{1/6}} X^{1/4}/|u|^{1/2} \\
& \leq X^{1/4} \sum_{0 < v \leq c_5^{1/2} X^{1/12}} \sum_{u \leq c_5^{1/6}/v^2} \frac{1}{|u|^{1/2}} \\
& \ll X^{1/3} \sum_{0 < v \leq c_5^{1/2} X^{1/12}} \frac{1}{v} \ll X^{1/3} \log X.
\end{align}

For the lower bound, we let $u, v, w$ range over positive, odd, squarefree numbers with $3 \mid w$ and let $a = uv^2$ and $A = uvw$ as in the previous paragraph; these ensure that conditions

\begin{align}
N(X) \geq \sum_{|u|v^2 \leq c_5 X^{1/6}} \sum_{|u|w^2 \leq c_6 X^{1/2}} 1 \ll \sum_{|u|v^2 \leq c_5 X^{1/6}} X^{1/4}/|u|^{1/2} \\
& \leq X^{1/4} \sum_{0 < v \leq c_5^{1/2} X^{1/12}} \sum_{u \leq c_5^{1/6}/v^2} \frac{1}{|u|^{1/2}} \\
& \ll X^{1/3} \sum_{0 < v \leq c_5^{1/2} X^{1/12}} \frac{1}{v} \ll X^{1/3} \log X.
\end{align}
(B1)–(B3) hold, so by Lemma 3.3 we have \( B \in \mathbb{Z} \). Conditions (N1) and (N4) are also satisfied, and condition (N3) is negligible. To ensure (N2), we choose

\[
v \leq X^{1/24}, \quad uv^2 < \frac{1}{2} X^{1/6}, \quad w < uw^3.
\]

Then \( A = uw < u^2v^4 < \frac{1}{4}X^{1/3} \) so \(|4A^3| \leq X\). Moreover,

\[
-12B = 3u^3v^6 + 6u^2v^3w - uw^2 = 3u^3v^6 \left(1 + 2\frac{w}{uv^3} - \frac{1}{3} \left(\frac{w}{uv^3}\right)^2\right)
\]

\[
< 3 \left(\frac{1}{2} X^{1/6}\right)^3 \frac{8}{3} = X^{1/2}
\]

since \(0 < w/uv^3 \leq 1 \) and the polynomial \(1 + 2t - \frac{1}{3}t^2\) on \([0,1]\) is positive and takes the maximum value \(\frac{8}{3}\). Thus, all conditions are satisfied.

We now count the choices for \(u, v, w\) with the above conditions: we have

\[
N(X) \geq \sum_{v \leq X^{1/24}} \sum_{uv^2 < \frac{1}{4}X^{1/6}} \sum_{w < uw^3} 1 \gg \sum_{v \leq X^{1/24}} \sum_{uv^2 < \frac{1}{4}X^{1/6}} uv^3.
\]

By partial summation, the inner sum on \(u\) is \(\gg X^{1/3}/v\), and then another partial summation gives that \(N_0(X) \gg X^{1/3}\log X\), which completes the proof of the lower bound. \(\square\)

4. An asymptotic

In this section, we prove an asymptotic for \(N(X)\).

We recall some notation introduced in the proof of Theorem 3.1. Let \((A, B, a) \in \mathbb{Z}^3\) satisfy (N1), so \(a \neq 0\) and \(B\) is determined by \(A, a\) as in Lemma 3.3. Write

\[
a = uv^2 \quad A = uw
\]

with \(u \in \mathbb{Z}\) squarefree, \(v \in \mathbb{Z}_{>0}\), and \(w \in \mathbb{Z}_{\neq 0}\). Then

\[
12B = uw^3 - 6u^2v^3w - 3u^3v^6.
\]

We rewrite condition (N4) and the conditions in Lemma 3.3 in terms of the quantities \(u, v, w\) as follows.

**Lemma 4.3.** Conditions (B1)–(B3) and (N4) hold if and only if all of the following conditions hold:

(W1) \(uv \equiv w \pmod{2}\);

(W2) Not both \(2^2 \mid v\) and \(2^4 \mid w\) occur;

(W3) Not all of \(2 \mid u, 2 \nmid v, \) and \(2^3 \nmid w\) occur;

(W4) Not all of \(2 \mid u, 2 \nmid v, \) and \(2^4 \nmid w\) occur;

(W5) \(3 \mid uw\);

(W6) Not both \(3 \mid v\) and \(3^4 \mid uw\) occur; and

(W7) For each prime \(\ell > 3\), not both \(\ell \mid v\) and \(\ell^3 \mid w\) occur.

**Proof.** This lemma can be proven by a tedious case-by-case analysis. Alternatively, the conditions (B1)–(B3) are determined by congruence conditions modulo 16 and 81, so we may also just loop over the possibilities by computer. \(\square\)
Lemma 4.4. The proportion among \((u, v, w)\) (with \(u\) squarefree) satisfying the conditions \((W1)–(W7)\) is \((4\zeta(4))^{-1}\).

Proof. For the conditions \((W1)–(W6)\), we just count residue classes (as in Lemma 4.3): we find proportions \(15/32\) for conditions \((W1)–(W4)\) and \(40/81\) for \((W5)–(W6)\). For condition \((W7)\), the proportion of cases where \(\ell|v\) and \(\ell^3|w\) is \(1/\ell^4\), thus the correction factor is

\[
\prod_{\ell>3} \left(1 - \frac{1}{\ell^4}\right) = \frac{16}{15} \cdot \frac{81}{80} \cdot \frac{1}{\zeta(4)} = \frac{27}{25\zeta(4)}.
\]

Thus the total proportion is

\[
\frac{15}{32} \cdot \frac{40}{81} \cdot \frac{27}{25\zeta(4)} = \frac{1}{4\zeta(4)}.
\]

Let \(X > 0\), and suppose \((A, B, a)\) is counted by \(N(X)\). Define \(\alpha, \beta \in \mathbb{R}_{>0}\) by

\[
a = uv^2 = \alpha X^{1/6},
\]

\[
w = \beta uv^3.
\]

(The quantity \(\alpha\) arose in the proof of Lemma 3.4.) Moreover, define the functions

\[
f(\beta) := \frac{1}{2^{1/3}|\beta|^{1/2}},
\]

\[
g(\beta) := \frac{4^{1/3}}{3^{1/2}|1 + 2\beta - \frac{1}{3}\beta^2|^{1/3}},
\]

\[
h(\beta) := \min\{f(\beta), g(\beta)\}.
\]
The transition points for the piecewise function \( h(\beta) \) occur at
\[
\beta_1 := 32.37198796 \ldots, \beta_2 := 1.7119188 \ldots, \beta_3 := -\frac{1}{3}, \beta_4 := -3;
\]
the transition points \( \beta_1, \beta_2 \) are algebraic numbers. Then \( h(\beta) = g(\beta) \) on the intervals \((-\infty, \beta_4), (\beta_3, \beta_2), \) and \((\beta_1, \infty) \) and \( h(\beta) = f(\beta) \) on the complementary intervals \((\beta_4, \beta_3)\) and \((\beta_2, \beta_1)\).

We compute numerically that
\[
c_0 := \int_{-\infty}^{\infty} h(\beta)^2 \, d\beta = 9.1812458638 \ldots.
\]

The relevance of these quantities (as well as their weighting) is made plain by the following lemma.

**Lemma 4.9.** The triple \((u, v, w)\) satisfies \((\text{N2})\) if and only if
\[
|\alpha| \leq h(\beta).
\]

**Proof.** Since \( A = uvw = \beta u^2 v^4 = \alpha^2 \beta X^{1/3} \), the first inequality in \((\text{N2})\) is equivalent to
\[
|\alpha^2 \beta| \leq 4^{-1/3}.
\]
In addition, we have
\[
-12B = 3u^3 v^6 \left(1 + 2w/uv^3 - \frac{1}{3} \left(\frac{w}{uv^3}\right)^2\right) = 3\alpha^3 X^{1/2} \left(1 + 2\beta - \frac{1}{3} \beta^2\right),
\]
so that the second inequality in \((\text{N2})\) is equivalent to
\[
|\alpha^3 \left(1 + 2\beta - \frac{1}{3} \beta^2\right)| \leq \frac{4}{3^{3/2}}.
\]
The result then follows from \((4.10)\) and \((4.11)\). \(\square\)

We then have the following first version of our main result.

**Theorem 4.12.** We have
\[
N(X) \sim c_1 X^{1/3} \log X
\]
where
\[
c_1 := \frac{c_0}{8 \pi^2 \zeta(4)} = 0.10743725502 \ldots
\]
and \(c_0\) is defined in \((4.8)\).

**Proof.** Via \((4.1)-(4.2)\), \(N(X)\) counts \((u, v, w) \in \mathbb{Z}^3\) with \(u\) squarefree, \(v\) positive, \(w \neq 0\), such that conditions \((\text{N2})-(\text{N3})\) hold as well as the local conditions \((\text{W1})-(\text{W7})\) (which implies \((\text{N4})\)). We may ignore condition \((\text{N3})\) as negligible: for each choice of \(u, v\) there are \(O(1)\) choices of \(w\) where \((\text{N3})\) fails, subtracting at most \(O(X^{1/6})\) from the count.

We first show how to count triples \(u, v, w\) satisfying \((\text{N2})\), not necessarily the local conditions, and define
\[
N_0(X) := \# \{(u, v, w) \in \mathbb{Z}^3 : u \text{ squarefree}, v > 0, \text{ and } (\text{N2}) \text{ holds}\}.
\]
We suppress the reminder that \(u\) is taken to be squarefree. The number of triples with \(w = 0\) is negligible, so we ignore this condition.
Let $X > 0$. For $(u, v, w)$ counted by $N_0(X)$, we organize by the value of $\beta = w/uv^3 \in \mathbb{Q}$. Taking $\beta$ in an interval $I$ of length $s$ that does not contain a transition point in its interior, the integers $u, v$ are constrained by

$$|a| = |u|v^2 < |\alpha|X^{1/6} < h(\beta)X^{1/6}$$

(with $h(\beta)$ minimal on $I$, taking left or right endpoint) by Lemma 4.9. Given $u, v$, we have $w = \beta uv^3 \in uv^3I$ giving approximately $uv^3$ possible values of $w$. Repeating this argument with Riemann sum estimates, we obtain

$$N_0(X) \sim \int_{-\infty}^{\infty} \sum_{|u|v^2 < h(\beta)X^{1/6}} |u|v^3 \, d\beta$$

as $X \to \infty$. (For a more refined approach with an error term, see (5.7) below.)

We now evaluate this integral. Recall that

$$\sum_{|u| \leq t} |u| \sim \frac{6}{\pi^2} t^2;$$

inputting this into (4.14) and letting $X \to \infty$, we obtain

$$\int_{-\infty}^{\infty} \sum_{v^2 < h(\beta)X^{1/6}} v^3 \sum_{|u| < h(\beta)X^{1/6}/v^2} |u| \, d\beta \sim \frac{6}{\pi^2} \int_{-\infty}^{\infty} \sum_{v < h(\beta)^{1/2}X^{1/12}} v^3 h(\beta)^2 X^{1/3} \, d\beta$$

$$\sim \frac{6X^{1/3}}{\pi^2} \int_{-\infty}^{\infty} h(\beta)^2 \int_{1}^{h(\beta)^{1/2}X^{1/12}} \frac{1}{v} \, dv \, d\beta$$

$$= \frac{6X^{1/3}}{\pi^2} \int_{-\infty}^{\infty} h(\beta)^2 \log(h(\beta)^{1/2}X^{1/12}) \, d\beta$$

$$\sim \frac{1}{2\pi^2} X^{1/3} \log X \int_{-\infty}^{\infty} \frac{h(\beta)^2 \, d\beta}{h(\beta)^2} = \frac{c_0}{2\pi^2} X^{1/3} \log X.$$

Finally, we impose the local constraints (W1)–(W7). The first 6 of these are clear. To impose (W7) note that

$$\frac{27}{25\zeta(4)} = \prod_{\ell > 3} \left(1 - \frac{1}{\ell^4}\right) = \sum_{\gcd(d,6) = 1} \frac{\mu(d)}{d^4}.$$ 

The sum converges rapidly, in fact, for $Z > 1$,

$$\left| \frac{27}{25\zeta(4)} - \sum_{\gcd(d,6) = 1, d \leq Z} \frac{\mu(d)}{d^4} \right| \ll \frac{1}{Z^3}.$$ 

Further, the proportion of triples $u, v, w$ with $d \mid v$ and $d^3 \mid w$ for some $d > Z$ tends to 0 as $Z \to \infty$. So, imposing (W7) introduces the factor $27/(25\zeta(4))$ as in Lemma 4.4. We conclude that

$$N(X) \sim \frac{1}{4\zeta(4)} N_0(X) \sim c_1 X^{1/3} \log X$$

as $X \to \infty$, as claimed. \qed
5. Secondary term

In this section, we work on a secondary term for $N(X)$ (giving a tertiary term for $N_3(X)$).

We start by explaining how this works for the function $N_0(X)$ defined in (4.13), namely, the triples $(u,v,w) \in \mathbb{Z}^3$ such that $u$ is squarefree, $v > 0$, and $|\alpha| \leq h(\beta)$ where $\alpha, \beta$ are defined by (4.5). We discuss the modifications to this approach for $N(X)$ below.

We begin by working out an analog of Euler’s constant for the squarefree harmonic series.

**Lemma 5.1.** For real numbers $x \geq 1$ we have
\[
\sum_{0 < u \leq x \atop u \text{ squarefree}} \frac{1}{u} = \frac{1}{\zeta(2)} \log x + \gamma_0 + O(x^{-1/2} \log x) = 1.0438945157\ldots,
\]
where
\[
(5.2) \quad \gamma_0 := \frac{\gamma \zeta(2) - 2\zeta'(2)}{\zeta(2)^2}
\]
and $\gamma$ is Euler’s constant.

**Proof.** The integer variables $u, v, d$ in this proof are positive. We have
\[
\sum_{u \leq x \atop u \text{ squarefree}} \frac{1}{u} = \sum_{d \leq x^{1/2}} \frac{\mu(d)}{d^2} \sum_{v \leq x/d^2} \frac{1}{v} = \sum_{d \leq x^{1/2}} \frac{\mu(d)}{d^2} \left( \log \left( \frac{x}{d^2} \right) + \gamma + O\left( \frac{d^2}{x} \right) \right).
\]
The $O$-terms add to $O(x^{-1/2})$. Since
\[
\sum_{d \leq x^{1/2}} \frac{\mu(d)}{d^2} = \sum_{d} \frac{\mu(d)}{d^2} - \sum_{d > x^{1/2}} \frac{\mu(d)}{d^2} = \frac{1}{\zeta(2)} + O(x^{-1/2})
\]
and
\[
\sum_{d \leq x^{1/2}} \frac{2\mu(d) \log d}{d^2} = \sum_{d} \frac{2\mu(d) \log d}{d^2} - \sum_{d > x^{1/2}} \frac{2\mu(d) \log d}{d^2} = \frac{2\zeta'(2)}{\zeta(2)^2} + O\left( x^{-1/2} \log x \right),
\]
the result follows. $\Box$

**Theorem 5.3.** We have
\[
N_0(X) = \frac{c_0}{2\pi^2} X^{1/3} \log X + c_6 X^{1/3} + O(X^{7/24})
\]
where $c_0$ is defined in (4.8) and
\[
(5.4) \quad c_6 := \left( \frac{\gamma_0}{2} + \frac{6\gamma}{\pi^2} - \frac{3}{2\pi^2} \right) c_0 + \frac{3}{\pi^2} \int_{-\infty}^{\infty} h(\beta)^2 \log h(\beta) \, d\beta = 1.12042819875\ldots
\]
where $\gamma_0$ is defined in (5.2) and $\gamma$ is Euler’s constant.

**Proof.** We return to the derivation of the integral expression (4.14) and consider the contribution of a single term $a = uv^2$. With $\alpha = a/X^{1/6}$, the contribution of $a$ to the integral is
\[
(5.5) \quad \int_{h(\beta) \geq |\alpha|} |u|v^3 \, d\beta = |u|v^3 \int_{h(\beta) \geq |\alpha|} d\beta.
\]
Note that $h$ is continuous. Let $h_1 := h_{(-\infty,-1/3]}$ and $h_2 := h_{[-1/3,\infty)}$. Then $h_1$ is strictly increasing and $h_2$ is strictly decreasing. Letting $j_1, j_2$ be the inverses of $h_1, h_2$, respectively, we have for any $t \in (0, h(-1/3)]$ that

$$
\{\beta \in \mathbb{R} : h(\beta) \geq t\} = [j_2(t), j_1(t)].
$$

Plugging (5.6) into the integral (5.5), we obtain

$$
(5.10)
$$

For a choice of $a = uv^2$, we count the number of nonzero integers $w$ with $w/(|u|v^3) \in [j_2(|\alpha|), j_1(|\alpha|)]$: this is equal to

$$
|u|v^3(j_1(|\alpha|) - j_2(|\alpha|)) + O(1).
$$

So, the error when considering the integral in (4.14) is $O(X^{1/6})$, i.e.,

$$
(5.7)
N_0(X) = \int_{-\infty}^{\infty} \sum_{\substack{|u|v^2 \leq h(\beta)X^{1/6} \\
v > 0}} |u|v^3 \, d\beta + O(X^{1/6}).
$$

We next consider the evaluation of the integrand

$$
(5.8)
S := \sum_{\substack{|u| v^2 < h(\beta)X^{1/6} \\
v > 0}} |u|v^3
$$

(with the continued understanding that $u$ is squarefree). Let $H(\beta) := h(\beta)^{1/4}X^{1/24}$, so that if $|u|v^2 \leq h(\beta)X^{1/6}$, then either $|u| \leq H^2$ or $v \leq H$. Let $S_1$ be the contribution to the integrand when $|u| \leq H^2$, let $S_2$ be the contribution when $v \leq H$, and let $S_3$ be the contribution when both $|u| \leq H^2$ and $v \leq H$. Then

$$
S = S_1 + S_2 - S_3.
$$

Using that $\sum_{0 < v \leq t} v^3 = \frac{1}{4} t^4 + O(t^3)$, for a given value of $u$ with $|u| \leq H^2$, we have

$$
\sum_{v \leq h(\beta)^{1/2}X^{1/12}/|u|^{1/2}} |u|v^3 = \frac{1}{4} |u| \left( \frac{h(\beta)^2 X^{1/3}}{|u|^2} + O\left( \frac{h(\beta)^{3/2} X^{1/4}}{|u|^{3/2}} \right) \right).
$$

Summing this over squarefree numbers $u$ with $|u| \leq H^2$ and using Lemma 5.1, we get

$$
S_1 = \frac{1}{4} h(\beta)^2 X^{1/3} \cdot 2 \left( \frac{6}{\pi^2} \log H^2 + \gamma_0 \right) + O\left( h(\beta)^2 X^{1/3} H^{-2} \log H + h(\beta)^{3/2} X^{1/4} H \right)
$$

$$
(5.9)
= \frac{1}{4\pi^2} h(\beta)^2 X^{1/3} \log X + h(\beta)^2 \left( \frac{1}{2} \gamma_0 + \frac{3}{2\pi^2} \log h(\beta) \right) X^{1/3}
$$

$$
+ O\left( h(\beta)^{3/2} X^{1/4} \log X \right) + O\left( h(\beta)^{7/4} X^{7/24} \right).
$$

Next we consider $S_2$. For a given value of $v \leq H$, we have

$$
S_2 = \sum_{\substack{|u| \leq h(\beta)X^{1/6}/v^2}} |u|v^3 = 2 \cdot \frac{1}{2} \cdot \frac{6}{\pi^2} h(\beta)^2 X^{1/3} v^{-1} + O\left( h(\beta)^{3/2} X^{1/4} \right).
$$

(5.10)
using that the number of squarefree numbers up to a bound \( x \) is \( \frac{6}{\pi^2}x + O(x^{1/2}) \) and partial summation. Summing for \( v \leq H \) we get

\[
S_2 = \frac{6}{\pi^2} h(\beta)^2 X^{1/3} \left( \frac{1}{24} \log X + \frac{\gamma}{4} + \frac{1}{4} \log h(\beta) + O(1/H) \right) + O(h(\beta)^{3/2}X^{1/4}H)
\]

(5.11)

\[
= \frac{1}{4\pi^2} h(\beta)^2 X^{1/3} \log X + \frac{6}{\pi^2} h(\beta)^2 \left( \frac{\gamma}{4} + \frac{1}{4} \log h(\beta) \right) X^{1/3} + O(h(\beta)^{7/4}X^{7/24}).
\]

Finally, for \( S_3 \) we have

\[
S_3 = \left( \frac{6}{\pi^2} H^4 + O(H^3) \right) \left( \frac{1}{4} H^4 + O(H^3) \right) = \frac{3}{2\pi^2} H^8 + O(H^7)
\]

(5.12)

\[
= \frac{3}{2\pi^2} h(\beta)^2 X^{1/3} + O(h(\beta)^{7/4}X^{7/24}).
\]

Since \( S = S_1 + S_2 - S_3 \), combining (5.12), (5.11), and (5.12) we obtain

\[
S = \frac{h(\beta)^2}{2\pi^2} X^{1/3} \log X + h(\beta)^2 \left( \frac{\gamma_0}{2} + \frac{6\gamma}{\pi^2} + \frac{3}{\pi^2} \log h(\beta) - \frac{3}{2\pi^2} \right) X^{1/3}
\]

\[\quad + O(h(\beta)^{3/2}X^{1/4} \log X) + O(h(\beta)^{7/4}X^{7/24}).\]

The expression (5.13) is then to be integrated over all \( \beta \) to obtain \( N_0(X) \) as in (5.7). However, in this integration, we may suppose that \( |\beta| \ll X^{1/4} \), since \( h(\beta) \ll |\beta|^{-2/3} \) and we may suppose that \( h(\beta)X^{1/6} \geq 1 \). Thus, integrating the first error term gives \( O(X^{1/4}(\log X)^2) \) and integrating the second error term gives \( O(X^{7/24}) \). We conclude that

\[
\int_{-\infty}^{\infty} \sum_{|u| \leq h(\beta)X^{1/6}} |u|v^2 d\beta = \frac{c_0}{2\pi^2} X^{1/3} \log X + \left( \frac{\gamma_0}{2} + \frac{6\gamma}{\pi^2} - \frac{3}{2\pi^2} \right) c_0 X^{1/3}
\]

(5.14)

\[\quad + \frac{3}{\pi^2} X^{1/3} \int_{-\infty}^{\infty} h(\beta)^2 \log h(\beta) d\beta + O(X^{7/24}).\]

We compute numerically that

\[
\int_{-\infty}^{\infty} h(\beta)^2 \log h(\beta) d\beta = -18.0878968694 \ldots
\]

and so the coefficient of the secondary term of \( N_0(X) \) is \( c_0 = 1.12042819875 \ldots \). \( \square \)

Before proving our main theorem, we prove one lemma, generalizing Lemma 5.1. For \( i \mid 6 \) with \( i > 0 \), let

\[
H_i(x) := \sum_{\substack{0 < u \leq x \atop u \text{ squarefree} \atop \gcd(u, 6) = i}} \frac{1}{u}.
\]

(5.16)

**Lemma 5.17.** We have

\[
H_1(x) = \frac{1}{2\zeta(2)} \log x + \gamma_1 + O\left( \frac{\log x}{x^{1/2}} \right)
\]

where

\[
\gamma_1 = \frac{\log 432}{24\zeta(2)} + \frac{\gamma}{12} - \frac{\zeta'(2)}{\zeta(2)^2},
\]

and

\[\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s} \quad \text{for} \quad s \in \mathbb{C} \cap \mathbb{R}_{> 1}, \quad \zeta(2) = \frac{\pi^2}{6}, \quad \zeta'(2) = -1.202056903159592749\ldots\]
and $\gamma$ is Euler’s constant. Moreover, $H_i(x) = \frac{1}{i} H_1(\frac{x}{i})$ for $i \mid 6$.

**Proof.** The proof follows the same lines as Lemma 5.1. □

We now prove our main result.

**Proof of Theorem 1.3.** The asymptotic for $N(X)$ was proven in Theorem 4.12 and a secondary term with power-saving error term for $N_0(X)$ was proven in Theorem 5.3. To finish, we claim that the local conditions (W1)–(W7) that move us from $N_0(X)$ to $N(X)$ can be applied in the course of the argument for Theorem 5.3 to obtain an (effectively computable) constant.

Let $i, j, k, d \in \mathbb{Z}_{>0}$ satisfy: $i \mid 6$, $d$ squarefree and coprime to 6, $j \mid 12$, and $k \mid 6^4$. Let $N_{i,j,k,d}(X)$ denote the number of triples $u, v, w$ counted by $N_0(X)$ with $\gcd(u, 6) = i$, $jd \mid v$, and $kd^3 \mid w$. Then with $i, j, k$ running over triples consistent with conditions (W1)–(W6), a signed sum of the counts $N_{i,j,k,d}(X)$ gives $N(X)$. For example, take the case of $uvw$ coprime to 6, which satisfies (W1)–(W6). The contribution of these triples to $N(X)$ is

$$\sum_{j \mid 6} \sum_{k \mid 6} \sum_{\gcd(d, 6) = 1} \mu(j) \mu(k) \mu(d) N_{1,j,k,d}(X).$$

We have similar expressions for other portions of the $u, v, w$-domain of triples.

We now estimate $N_{i,j,k,d}$ and control the contribution to $N(X)$ from large $d$. For the latter, since $|vw| \leq A \ll X^{1/3}$, we have $d \ll X^{1/12}$; so we may suppose that $d$ is so bounded. Getting a good estimate for $N_{i,j,k,d}$ follows in exactly the same way as with $N_0$. In particular, we have the analogue of (5.7):

$$(5.18) \quad N_{i,j,k,d}(X) = \int_{-\infty}^{\infty} \sum_{\substack{|u|v^2 \leq h(\beta)X^{1/6} \\gcd(u, 6) = i \\gcd(v, 6) = 1 \\gcd(d, 6) = 1 \\gcd(u, v, 6) = 1}} \frac{|u|v^3}{kd^3} d\beta + O(X^{1/6}),$$

where it is understood that $u$ is squarefree and $v > 0$. The sum here is estimated in the same way, by first considering the contribution when $|u| \leq H^2$, where $H = h(\beta)X^{1/24}$, then the contribution when $v \leq H$, and finally the contribution when both $|u| \leq H^2$ and $v \leq H$. To accomplish this, we use the following asymptotic estimates:

$$(5.19) \quad \sum_{0 < v \leq x \atop jd \mid v} v^3 = \frac{1}{4} \frac{x^4}{jd} + O(x^3), \quad \sum_{0 < v \leq x \atop jd \mid v} \frac{1}{v} = \frac{1}{jd} \log x + \frac{\gamma - \log(jd)}{jd} + O\left(\frac{1}{x^{1/2}d^{1/2}}\right), \quad \sum_{|u| \text{ squarefree} \atop |u| \leq x \atop \gcd(u, 6) = i} |u| = \frac{1}{i \zeta(2)} x^2 + O(x^{3/2}).$$

We also need the sum of $1/|u|$, accomplished in Lemma 5.17.
Putting these ingredients together, we get that
\begin{equation}
N_{i,j,k,d}(X) = \frac{c_{i,j,k}}{d^4} X^{1/3} \log X + \frac{c'_{i,j,k}}{d^4} X^{1/3} + O\left(\frac{X^{7/24}}{d^3}\right),
\end{equation}
where \(c_{i,j,k}, c'_{i,j,k} = O(1)\) uniformly, and summing these contribution gives the result. \(\square\)

6. Computations

We conclude with some computations that give numerical verification of our asymptotic expression.

We computed the functions \(N_0(X)\) and \(N(X)\) as follows. First, we restrict to \(u > 0\) (still squarefree), since this gives exactly half the count. Second, we loop over \(u\) up to \(\left\lfloor \frac{11}{8} X^{1/6} \right\rfloor\) (valid as in the proof of Lemma 3.4) and keep only squarefree \(u\). Then we loop over \(v\) from 0 up to \(\left\lfloor \sqrt{\frac{11}{8} X^{1/6}/u} \right\rfloor\). This gives us the value of \(a = uv^2\). Then plugging into \(h\) gives
\begin{equation}
\beta_{\text{max}} \leq \max\left(\left\{ \frac{X^{1/3}}{4^{1/3}a^2}, 3 + \sqrt{12 + \frac{4}{\sqrt{3}} \frac{X^{1/2}}{a^3}} \right\} \right).
\end{equation}
Then we loop over \(w\) from \(-\beta_{\text{max}} uv^3\) to \(\beta_{\text{max}} uv^3\), ignoring \(w = 0\), and we take \(A = uvw\). We then check that \(|4A^3| \leq X\); and letting
\[ B = \frac{1}{12} \left( \frac{A^2}{a} - 6Aa - 3a^3 \right) \]
we check that \(|27B^2| \leq X\), and if so add to the count for \(N_0(X)\). For \(N(X)\), we further check the local conditions (B1)–(B3) and (N4) (or, equivalently, (W1)–(W7)).

In this manner, we thereby compute the data in Table 6.4 for \(X = 10^m\): we computed \(N_0(10^m)\) for \(m \leq 20\) and \(N(10^m)\) for \(m \leq 25\).

A best fit with
\[ N_0(X) \approx c_7 X^{1/3} \log(X) + c_8 X^{1/3} \]
confirms
\begin{align}
c_7 & = 0.46527 \approx 0.46513 \ldots = \frac{c_0}{2\pi^2} \\
c_8 & = 1.1121 \approx 1.1204 \ldots = c_6
\end{align}
and the difference between the first two columns is indeed small. Similarly, a best fit with
\[ N(X) \approx c_9 X^{1/3} \log(X) + c_{10} X^{1/3} \]
gives
\begin{align}
c_9 & = 0.107400 \approx 0.107437 \ldots = c_1 \\
c_{10} & = 0.165612 \approx c_2
\end{align}
confirms the asymptotic, with an approximate value for the constant \(c_2 \approx 0.16\) as also indicated in the fourth column.
\[
\begin{array}{c|c|c|c|c|c}
\hline
m & N_0(X) & \frac{c_0}{2\pi^2}X^{1/3}\log(X) + c_0X^{1/3} & N(X) & \frac{N(X) - c_1X^{1/3}\log X}{X^{1/3}} \\
\hline
3 & 40 & 43 & 2 & -0.54215 \\
4 & 106 & 116 & 16 & -0.24688 \\
5 & 292 & 301 & 54 & -0.07352 \\
6 & 728 & 755 & 144 & -0.04430 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
16 & 3931970 & 3933212 & 887334 & 0.16051 \\
17 & 8968482 & 8970960 & 2026332 & 0.16008 \\
18 & 20396372 & 20398344 & 4615666 & 0.16276 \\
19 & 46250606 & 46254289 & 10476028 & 0.16226 \\
20 & 104614810 & 104622964 & 23720904 & 0.16285 \\
21 & 236105316 & 236113295 & 53583854 & 0.16333 \\
22 & 531764374 & 531764568 & 120772894 & 0.16335 \\
23 & 1195334414 & 1195363230 & 271694240 & 0.16366 \\
24 & 2682372754 & 2682431541 & 610085848 & 0.16366 \\
25 & 6009687100 & 6009862508 & 1367646478 & 0.16347 \\
\end{array}
\]

Table 6.4: Data before and after applying local conditions

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