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On the ubiquity of trivial torsion on elliptic curves

Enrique González-Jiménez and José M. Tornero

Abstract. The purpose of this paper is to give a *down-to-earth* proof of the well-known fact that a randomly chosen elliptic curve over the rationals is most likely to have trivial torsion.

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1. Introduction. Let us consider an elliptic curve E, defined over the rationals and written in short Weierstrass form

$$E : Y^2 = X^3 + AX + B, \quad A, B \in \mathbb{Z}. \tag{1}$$

We will use the standard notations for:

- $\Delta = -16(4A^3 + 27B^2) \neq 0$, the discriminant of E;
- $E(\mathbb{Q})$, the finitely generated abelian group of rational points on E, and
- $\mathcal{O}$, the identity element of $E(\mathbb{Q})$.

Given $P \in E(\mathbb{Q})$, we will also write as customary $[m]P$ for the point resulting after adding m times P.

The problem of computing the torsion of $E(\mathbb{Q})$ has been solved in a lot of very efficient ways [2,3,6], and most computer packages (say `Maple-Apecs`, `PARI/GP`, `Magma` or `Sage`) calculate the torsion of curves with huge coefficients in a few seconds. The major result which made this possible [along with others, like the Nagell–Lutz Theorem [18,15] or the embedding theorem for good reduction primes (see, for example, [21, VIII.7] or [12, Chapter 5])] was Mazur's Theorem [16,17], who listed the fifteen possible torsion groups.

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In the above papers, it is proved that the possible structures of the torsion group of $E(\mathbb{Q})$ are

$$\mathbb{Z}/n\mathbb{Z} \text{ for } n = 2, \ldots, 10, 12, \quad \text{or} \quad \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2n\mathbb{Z} \text{ for } n = 1, \ldots, 4.$$

Besides, the fifteen of them actually happen as torsion subgroups of elliptic curves. Notice that thanks to the above theorem, the possible prime orders for a torsion point defined over $\mathbb{Q}$ are $2, 3, 5$, or 7.

Let p be a prime number and let $E[p]$ be the group of points of order p on $E(\overline{\mathbb{Q}})$, where $\overline{\mathbb{Q}}$ denotes an algebraic closure of $\mathbb{Q}$. The action of the absolute Galois group $\mathrm{G}_{\mathbb{Q}} = \mathrm{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$ on $E[p]$ defines a mod p Galois representation

$$\rho_{E,p} : \mathrm{G}_{\mathbb{Q}} \to \mathrm{Aut}(E[p]) \cong \mathrm{GL}_2(\mathbb{F}_p).$$

Let $\mathbb{Q}(E[p])$ be the number field generated by the coordinates of the points of $E[p]$. Therefore, the Galois extension $\mathbb{Q}(E[p])/\mathbb{Q}$ has Galois group

$$\mathrm{Gal}(\mathbb{Q}(E[p])/\mathbb{Q}) \cong \rho_{E,p}(\mathrm{G}_{\mathbb{Q}}).$$

The prime p is called exceptional for E if $\rho_{E,p}$ is not surjective. If E has complex multiplication then any odd prime number is exceptional. On the other hand, if E does not have complex multiplication then Serre [20] proved that E has only finitely many exceptional primes.

Duke [4] proved that *almost all* elliptic curves over $\mathbb{Q}$ have no exceptional primes. More precisely, given an elliptic curve E in a short Weierstrass form as in (1), the height of the elliptic curve is defined as

$$H(E) = \max(|A|^3, |B|^2).$$

Let M be a positive integer, and let $\mathcal{C}_H(M)$ be the set of elliptic curves E with $H(E) \leq M^6$. For any prime p denote by $\mathcal{E}_p(M)$ the set of elliptic curves $E \in \mathcal{C}_H(M)$ such that p is an exceptional prime for E, and by $\mathcal{E}(M)$ the union of $\mathcal{E}_p(M)$ for all primes. Actually in both sets the elliptic curves were considered up to $\mathbb{Q}$-isomorphisms. Duke then proved that

$$\lim_{M \to \infty} \frac{|\mathcal{E}(M)|}{|\mathcal{C}_H(M)|} = 0.$$

His proof is based on a version of the Chebotarev density theorem, and uses a two-dimensional large sieve inequality together with results of Deuring, Hurwitz, and Masser and Wüstholz.

Duke also conjectured the following fact, later proved by Grant [10]

$$|\mathcal{E}(M)| \sim c\sqrt{M}.$$

Being a bit more precise, Grant showed that, in order to efficiently estimate $|\mathcal{E}(M)|$, only $\mathcal{E}_2(M)$ and $\mathcal{E}_3(M)$ had to be actually taken into account.

Now recall that there is a tight relationship between exceptional primes and torsion orders, because if there is a point of order p, then p is an exceptional prime [20]. Our aim is then giving a down-to-earth proof of the fact that *almost all* elliptic curves over $\mathbb{Q}$ have trivial torsion, motivated by Duke's paper.

In order to achieve this, we will use the characterization of torsion structures given in [7,8], Mazur's Theorem [16,17]; and a theorem by Schmidt [19] on Thue inequalities. Note that we have used a different height notion, more naive in some sense, but nevertheless better suited for our purposes.

Let us change a bit the notation and let us call

$$E_{(A,B)} : \; Y^2 = X^3 + AX + B$$

and, provided $\Delta \neq 0$, we will denote by $E_{(A,B)}(\mathbb{Q})[m]$ the group of points $P \in E_{(A,B)}(\mathbb{Q})$ such that $[m]P = \mathcal{O}$. Let us write as well

$$\mathcal{C}(M) = \{(A,B) \in \mathbb{Z}^2 \mid \Delta = -16(4A^3 + 27B^2) \neq 0, \;\; |A|, |B| \leq M\}.$$
$$\mathcal{T}_p(M) = \{(A,B) \in \mathcal{C}(M) \mid E_{(A,B)}(\mathbb{Q})[p] \neq \{\mathcal{O}\}\}.$$
$$\mathcal{T}(M) = \bigcup_{p \text{ prime}} \mathcal{T}_p(M)$$

Our version of Duke's result is then as follows.

Theorem 1.1. *With the notations above,*

$$\lim_{M \to \infty} \frac{|\mathcal{T}(M)|}{|\mathcal{C}(M)|} = 0.$$

The proof will lead to extremely coarse bounds for $|\mathcal{T}_p(M)|$ which will be proved unsatisfactory in view of experimental data, which we will display subsequently.

2. Proof of Theorem 1.1. Recall that the possible prime orders of a torsion point defined over $\mathbb{Q}$ are $2, 3, 5$ or 7.

We will make extensive use of the parametrizations of curves with a point of prescribed order given in [7,8,14]. These results have recently been proved useful in showing new properties of the torsion subgroup (see, for instance [1,9,13]).

First, note that, for a given A with $|A| \leq M$ there are, at most, two possible choices for B such that $\Delta = 0$ (and hence, the corresponding curve $E_{(A,B)}$ is not an elliptic curve). Therefore

$$|\mathcal{C}(M)| \geq (2M+1)^2 - 2(2M+1) = 4M^2 - 1.$$

Let us recall from [7] that a curve $E_{(A,B)}$ with a point of order 2 must verify that there exist $z_1, z_2 \in \mathbb{Z}$ such that

$$A = z_1 - z_2^2, \quad B = z_1 z_2.$$

Therefore $z_1 | B$ and for a chosen z_1, both z_2 and A are determined. Hence, there is at most one pair in $\mathcal{T}_2(M)$ for every divisor of B.

We need now an estimate for the average order of the function $d(x)$, the number of positive divisors of x. The simplest estimation is, probably, the one that can be found in [11],

$$d(1) + d(2) + \cdots + d(x) \sim x \log(x).$$

As M tends to infinity,

$$|\mathcal{T}_2(M)| \leq \sum_{x=1}^{M} 2d(x) + \sum_{x=1}^{M} 2d(x) + 2M,$$

taking into account that we need to consider both positive and negative divisors, the cases where $x \in \{-M, \dots, -1\}$ and the $2M$ curves with $B = 0$. Hence $|\mathcal{T}_2(M)| \leq c_2 M \log(M)$, where we can, in fact, take $c_2 = 4$.

As for points of order 3 we can find in [7] a similar characterization (a bit more complicated this time) based on the existence of $z_1, z_2 \in \mathbb{Z}$ such that

$$A = 27z_1^4 + 6z_1z_2, \quad B = z_2^2 - 27z_1^6.$$

Analogously $z_1|A$ and, once we fix such a divisor, z_2 is necessarily given by

$$z_2 = \frac{A - 27z_1^4}{6z_1},$$

which implies that again there is at most one pair in $\mathcal{T}_3(M)$ for every divisor of A. Hence, as M tends to infinity

$$|\mathcal{T}_3(M)| \leq c_3 M \log(M),$$

and again $c_3 = 4$ suits us.

Points of order 5 and 7 need a similar, yet slightly different argument. From [8] we know that if there is a point of order 5 in $E_{(A,B)}(\mathbb{Q})$, then there must exist $p, q \in \mathbb{Z}$ verifying:

$$\begin{aligned} A &= -27(q^4 - 12q^3p + 14q^2p^2 + 12p^3q + p^4), \\ B &= 54(p^2 + q^2)(q^4 - 18q^3p + 74q^2p^2 + 18p^3q + p^4). \end{aligned}$$

The first equation is an irreducible Thue equation, hence we can apply the following result by Schmidt:

Theorem 2.1 (Schmidt [19]). *Let $F(x, y)$ be an irreducible binary form of degree $r > 3$, with integral coefficients. Suppose that not more than $s + 1$ coefficients are nonzero. Then the number of solutions of the inequality $|F(x, y)| \leq h$ is, a most,*

$$(rs)^{1/2} h^{2/r} \left(1 + \log^{1/r}(h)\right).$$

In our situation, this gives a bound for the number of possible (p, q) such that

$$\left|-27(q^4 - 12q^3p + 14q^2p^2 + 12p^3q + p^4)\right| \leq M.$$

Hence, as every such solution determines at most one pair in $\mathcal{T}_5(M)$,

$$|\mathcal{T}_5(M)| \leq 4\sqrt{M} \left(1 + \log^{1/4}(M)\right).$$

A similar result can be applied for points of order 7. The equations which must have a solution are now

$$\begin{aligned} A = &-27k^4(p^2 - pq + q^2)(q^6 + 5q^5p - 10q^4p^2 - 15q^3p^3 \\ &+30q^2p^4 - 11qp^5 + p^6), \\ B = &\,54k^6(p^{12} - 18p^{11}q + 117p^{10}q^2 - 354p^9q^3 + 570p^8q^4 - 486p^7q^5 \\ &+273p^6q^6 - 222p^5q^7 + 174p^4q^8 - 46p^3q^9 - 15p^2q^{10} + 6pq^{11} + q^{12}). \end{aligned}$$

either for $k = 1$ or for $k = 1/3$. Hence, using the polynomial defining B and with a similar argument as above

$$|\mathcal{T}_7(M)| \leq 24\sqrt[6]{M}\left(1 + \log^{1/12}(M)\right).$$

Therefore, for all p there is an absolute constant $c_p \in \mathbb{Z}_+$ such that

$$\lim_{M\to\infty} \frac{|\mathcal{T}_p(M)|}{|C(M)|} \leq \lim_{M\to\infty} \frac{c_p M \log(M)}{4M^2 - 1} = 0.$$

This proves the theorem.

Remark 2.2. It must be noted here that our arguments are counting pairs (A, B). So, in fact, isomorphic curves may appear as separated cases. Both Duke and Grant estimated isomorphism classes (over $\mathbb{Q}$) rather than curves.

But this can also be achieved by the arguments above with a little extra work. We will show now that these instances of isomorphic curves are actually negligible as far as counting is concerned.

First note that if two curves $E_{(A,B)}$ and $E_{(A',B')}$ are isomorphic over $\mathbb{Q}$, there must be some $u \in \mathbb{Q}$ such that $A = u^4 A'$ and $B = u^6 B'$. Hence, there exists some prime l such that, say, $l^4|A$ and $l^6|B$ (the case $l^4|A'$ and $l^6|B'$ is analogous). Let us write, for a fixed prime l

$$P_n(M, l) = \{x \in \mathbb{Z}_+ \mid 1 \leq x \leq M,\ \ l^n|M\},$$

and by $P_n(M)$ the union of $P_n(M, l)$, where l run the set of prime divisors of M.

Then it is clear that

$$|P_n(M^n)| \leq \sum_{l\leq M} |P_n(M^n, l)| = \sum_{l\leq M} \left[\frac{M^n}{l^n}\right] = \sum_{l\leq M}\left(\frac{M^n}{l^n} + O(1)\right)$$
$$= M^n \sum_{l\leq M}\left(\frac{1}{l^n}\right) + O(M) = M^n \sum_{l \text{ prime}} \frac{1}{l^n} + O(M) = M^n\mathcal{P}(n) + O(M),$$

where $\mathcal{P}$ is the prime zeta function (see [5], for instance). So, asymptotically

$$|P_4(M)| \leq P(4)M + O\left(\sqrt[4]{M}\right) \simeq 0.0769931M + O\left(\sqrt[4]{M}\right),$$
$$|P_6(M)| \leq P(6)M + O\left(\sqrt[6]{M}\right) \simeq 0.0170701M + O\left(\sqrt[6]{M}\right).$$

Hence, if we are interested in curves up to $\mathbb{Q}$-isomorphism, our bounds for $|\mathcal{T}_p(M)|$ are still correct, while we should replace

$$|\mathcal{C}(M)| \geq 4M^2 - 1$$

by

$$|\mathcal{C}(M)| \geq (4 - P(4)P(6))M^2 + O\left(\sqrt[6]{M}\right)$$

which obviously makes no difference in the result.

Remark 2.3. While all of our bounds for $|\mathcal{T}_p(M)|$ are of the form $c_p M \log(M)$, computational data show that the actual number of curves on $\mathcal{T}_p(M)$ depends heavily on p, as one might predict after the estimate given by Grant [10] for $\mathcal{E}_p(M)$, the set of elliptic curves $E \in \mathcal{C}_H(M)$ such that p is an exceptional prime for E. In fact, a hands-on `Magma` program gave us the following output

M	$\lvert\mathcal{T}_2(M)\rvert$	$\lvert\mathcal{T}_3(M)\rvert$	$\lvert\mathcal{T}_5(M)\rvert$	$\lvert\mathcal{T}_7(M)\rvert$
10^4	$204,220$	507	1	1
10^5	$2,484,196$	$1,935$	3	1
10^6	$29,430,050$	$5,873$	11	4
10^7	$340,334,782$	$18,387$	24	5

These actual figures are much smaller than the bounds obtained.

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Enrique González-Jiménez
Departamento de Matemáticas,
Universidad Autoónoma de Madrid and Instituto de Ciencias Matemáticas
(CSIC-UAM-UC3M-UCM),
28049 Madrid, Spain
e-mail: enrique.gonzalez.jimenez@uam.es

José M. Tornero
Departamento de Álgebra,
Universidad de Sevilla,
P.O. 1160,
41080 Sevilla, Spain
e-mail: tornero@us.es

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