

## Comparing multiplicative orders mod $p$ , as $p$ varies

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ABSTRACT. Schinzel and Wójcik have shown that if  $\alpha, \beta$  are rational numbers not 0 or  $\pm 1$ , then  $\text{ord}_p(\alpha) = \text{ord}_p(\beta)$  for infinitely many primes  $p$ , where  $\text{ord}_p(\cdot)$  denotes the order in  $\mathbb{F}_p^\times$ . We begin by asking: When are there infinitely many primes  $p$  with  $\text{ord}_p(\alpha) > \text{ord}_p(\beta)$ ? We write down several families of pairs  $\alpha, \beta$  for which we can prove this to be the case. In particular, we show this happens for “100%” of pairs  $A, 2$ , as  $A$  runs through the positive integers. We end on a different note, proving a version of Schinzel and Wójcik’s theorem for the integers of an imaginary quadratic field  $K$ : If  $\alpha, \beta \in \mathcal{O}_K$  are nonzero and neither is a root of unity, then there are infinitely many maximal ideals  $P$  of  $\mathcal{O}_K$  for which  $\text{ord}_P(\alpha) = \text{ord}_P(\beta)$ .

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### 1. Introduction

Let  $\alpha, \beta$  be rational numbers, not 0 or  $\pm 1$ . For all but finitely many primes  $p$ , both  $\alpha$  and  $\beta$  are  $p$ -adic units, and so it is sensible to talk about their multiplicative orders upon reduction mod  $p$ . Schinzel and Wójcik [SW92], extending unpublished investigations of J.S. Wilson, J.G. Thompson, and J.W.S. Cassels, proved that there are infinitely many primes  $p$  for which  $\text{ord}_p(\alpha) = \text{ord}_p(\beta)$ . Equivalently (since  $\mathbb{F}_p^\times$  is cyclic),  $\alpha$  and  $\beta$  generate the same subgroup of  $\mathbb{F}_p^\times$  infinitely often.

Received February 5, 2021.

2010 *Mathematics Subject Classification*. Primary 11A07, 11R11; Secondary 11A15.

*Key words and phrases*. multiplicative order, support problem, Schinzel–Wójcik problem, anti-elite prime, anti-elite number, order-dominant pair.

It is an open problem to characterize the triples  $\alpha, \beta, \gamma \in \mathbb{Q}^\times \setminus \{\pm 1\}$  for which  $\text{ord}_p(\alpha) = \text{ord}_p(\beta) = \text{ord}_p(\gamma)$  infinitely often. But in a recent preprint, Järviemi presents such a characterization not just for triples, but for tuples of any fixed length, conditional on the Generalized Riemann Hypothesis [Jä20]. (See [PS09] for earlier GRH-conditional results, and [Wój96, Fou18] for related results conditional not on GRH but on Schinzel’s “Hypothesis H” [SS58].) Sticking instead to pairs  $\alpha, \beta$  but taking the problem in a different direction, various authors have investigated the distribution of  $p$  for which  $\text{ord}_p(\alpha) \mid \text{ord}_p(\beta)$  (see [MS00] and [MuSS19]).

It is known that if  $\alpha, \beta \in \mathbb{Q}^\times \setminus \{\pm 1\}$  and  $\text{ord}_p(\alpha) = \text{ord}_p(\beta)$  for all but finitely many primes  $p$ , then  $\alpha = \beta$  or  $\alpha = \beta^{-1}$  (see [Sch70] or [CRnS97]). A natural complement to the theorem of Schinzel and Wójcik would be a characterization of those pairs  $\alpha, \beta \in \mathbb{Q}^\times \setminus \{\pm 1\}$  for which

$$\text{ord}_p(\alpha) > \text{ord}_p(\beta) \quad \text{for infinitely many primes } p. \tag{1}$$

Call the (ordered) pair  $\alpha, \beta$  *order-dominant* if (1) holds.

Under GRH, we have a completely satisfactory classification of order-dominant pairs. Assume, as above, that  $\alpha, \beta \in \mathbb{Q}^\times \setminus \{\pm 1\}$ . Then  $\alpha, \beta$  is order-dominant if and only if  $\alpha$  is not a power of  $\beta$ .<sup>1</sup> It seems difficult to obtain a result of comparable strength unconditionally. Our first three theorems describe partial progress. Each reports on certain families of integers  $A, B$  for which we can prove the order-dominance of  $A, B$  without any unproved hypothesis. We mostly (but not exclusively) restrict attention to positive integers  $A, B$ ; this allows us to illustrate the basic methods while avoiding technical complications. As will become clear shortly, the limitations of our methods manifest already in this restricted situation; given these limitations, we have tried optimize the exposition for clarity rather than generality.

Below,  $(\cdot)$  denotes the Legendre–Jacobi–Kronecker symbol.

**Theorem 1.1.**

- (i) *Let  $A, B$  be odd positive integers. Then  $A, B$  is order-dominant if either*

$$\left(\frac{-B(1-B)}{A}\right) = -1 \quad \text{or} \quad \left(\frac{1-B}{A}\right) = -1.$$

- (ii) *The pair  $2, B$  is order-dominant for every odd positive integer  $B$ .*
- (iii) *The pair  $A, 2$  is order-dominant for every odd positive integer  $A$  with  $\left(\frac{-1}{A}\right) = -1$  or  $\left(\frac{-2}{A}\right) = -1$ , i.e., all odd positive  $A \not\equiv 1 \pmod{8}$ .*

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<sup>1</sup>The “only if” half is clear. For the “if” direction: When  $\alpha, \beta$  are multiplicatively independent, Järviemi [Jä20, Theorem 1.4] proves (under GRH) that  $\text{ord}_p(\alpha)/\text{ord}_p(\beta)$  can be made arbitrarily large, which certainly implies the order-dominance of  $\alpha, \beta$ . When  $\alpha, \beta$  are multiplicatively dependent but  $\alpha$  is not a power of  $\beta$ , the order-dominance of  $\alpha, \beta$  follows (unconditionally) from an elementary argument with Zsigmondy’s theorem.

- (iv) *If  $A, B$  are coprime positive integers with  $B > A^4$ , then  $-A, B$  is order-dominant.*

For example, it follows from Theorem 1.1 and its proof (see Remark 2.1(ii)) that if  $A$  and  $B$  are any of 2, 3, 5, or 7, and  $A \neq B$ , then there are infinitely many primes  $p$  with  $\text{ord}_p(A) > \text{ord}_p(B)$ .

When  $(A, B) \in \{(2, 3), (3, 2), (2, 5), (5, 2)\}$ , Theorem 1.1 was implicitly proved by Banaszak in [Ban98] (see the proofs of Theorems 1 and 2 in [Ban98]), although his results were not stated this way. Our proofs are essentially the same as his for these cases.

Theorem 1.1(iii) leaves untouched the pairs  $A, 2$  with  $A \equiv 1 \pmod{8}$ . We can show that most such pairs are order-dominant. In fact, we have the following stronger result.

**Theorem 1.2.** *The pair  $A, 2$  is order-dominant for almost all positive integers  $A$ , meaning that the set of exceptional  $A$  has asymptotic density 0.*

(Note that Theorem 1.2, unlike Theorem 1.1(iii), allows  $A$  to be even.) The proof of Theorem 1.2 begins by establishing an explicit (though slightly technical) sufficient condition for  $A, 2$  to be order-dominant, involving properties of Fermat numbers. The  $A$  for which this condition fails, which we term *anti-elite numbers*, are then shown to be rare. See Remark 3.3 for the list of anti-elite  $A$  up to 150.

The proofs of Theorems 1.1 and 1.2, when they succeed, prove more than the order-dominance of  $\alpha, \beta$ . For all the pairs handled there, what is actually proved is that for infinitely many primes  $p$ , the ratio  $\text{ord}_p(\alpha)/\text{ord}_p(\beta)$  is a positive even integer. Evenness stems from the fact that the primes  $p$  we produce have  $\alpha$  not a square modulo  $p$ , which we detect by quadratic reciprocity. One might hope to use higher reciprocity laws to generate further examples of order-dominant pairs. Our next theorem, whose proof depends on cubic reciprocity, is a modest step in this direction.

**Theorem 1.3.** *Let  $A$  be an integer for which  $3 \nmid A$  and  $A^2 \not\equiv 1 \pmod{9}$ . For infinitely many primes  $p$ , the ratio  $\text{ord}_p(A)/\text{ord}_p(-3)$  is an integer multiple of 3. Thus, both  $A, -3$  and  $A, 3$  are order-dominant.*

(To see the claim about  $A, 3$ , observe that  $\text{ord}_p(3)$  is at most twice  $\text{ord}_p(-3)$ , and so at most two-thirds of  $\text{ord}_p(A)$ .) Unfortunately, the proof of Theorem 1.3 is not very amenable to generalization, although certain other pairs with  $B = \pm 3\Box$  (i.e.,  $\pm 3$  times a square) could be treated in a similar fashion. Analogously, the law of biquadratic reciprocity could be used to establish order-dominance of certain pairs  $A, B$  with  $B = -\Box$ .

One consequence of Theorem 1.3 is that the pair 4, 3 is order-dominant. This could certainly not be proved by the methods of Theorem 1.1 or 1.2, since 4 is a square modulo every  $p$ .

Theorems 1.1, 1.2, and 1.3 (as well as their methods of proof) still leave us quite far from the GRH-conditional characterization of order dominant

pairs. An interesting, difficult-seeming test case is the problem of proving that

$$\text{ord}_p(17) > \text{ord}_p(2) \quad \text{for infinitely many primes } p.$$

We hope that interested readers will take up this challenge!

Our final theorem is of a quite different nature. We prove the analogue of Schinzel and Wójcik’s result for the integers of an imaginary quadratic field.

**Theorem 1.4.** *Let  $K$  be an imaginary quadratic field with ring of integers  $\mathcal{O}_K$ . For nonzero  $\alpha, \beta \in \mathcal{O}_K$ , neither of which is a root of unity, there are infinitely many prime ideals  $P$  of  $\mathcal{O}_K$  for which  $\alpha$  and  $\beta$  generate the same subgroup of  $(\mathcal{O}_K/P)^\times$ .*

For example,  $1 + i$  and  $2 + i$  generate the same subgroup of  $(\mathbb{Z}[i]/(\pi))^\times$  for infinitely many Gaussian primes  $\pi$ .

While the proof of Theorem 1.4 follows the same basic strategy as [SW92], there are essential differences. It is important for us to have available auxiliary primes  $\ell$  for which the  $\ell$ th power map, mod  $\ell$ , is induced by a nontrivial automorphism of  $K$ . In fact, we will use that all primes  $\ell \equiv -1 \pmod{\Delta}$  have this property, where  $\Delta$  is the discriminant of  $K$ ; this explains the requirement in the theorem that  $K$  is imaginary.

It would be interesting to relax the restriction in Theorem 1.4 that  $\alpha$  and  $\beta$  be integers of the field  $K$ . While our method of proof works for many pairs of nonintegral  $\alpha, \beta \in K$ , an elegant general statement does not seem forthcoming by these arguments.

**Notation and conventions.** Since  $\text{ord}_P(\cdot)$  is being used for the multiplicative order mod  $P$ , the  $P$ -adic valuation will be denoted  $v_P(\cdot)$ . We use  $\lambda(\cdot)$  for Carmichael’s function; that is,  $\lambda(n)$  is the exponent of the multiplicative group mod  $n$ . We write  $\langle g \rangle$  for the cyclic subgroup generated by a group element  $g$ .

We say that a statement about positive integers  $n$  holds **whenever**  $n$  is sufficiently divisible if there is a positive integer  $K$  such that the statement holds for all  $n$  divisible by  $K!$ . Note that if each of two statements holds whenever  $n$  is sufficiently divisible, then their conjunction holds for all sufficiently divisible  $n$ . One should think of the requirement that  $n$  be sufficiently divisible as analogous to the condition, in real analysis, that  $\epsilon$  be sufficiently close to 0. In fact, this is a bit more than an analogy: Asking that  $n$  be sufficiently divisible amounts precisely to asking that  $n$  be close enough to 0 in  $\hat{\mathbb{Z}}$ , the profinite completion of the integers.

The requirement of sufficient divisibility will come up in the following way. We have a commutative ring  $R$ , an ideal  $I$  for which  $R/I$  is finite, and an element  $A \in R$  that is invertible modulo  $I$ . Then  $A^n \equiv 1 \pmod{I}$  whenever  $n$  is sufficiently divisible. Of course, it is simple enough here to say that the congruence holds whenever  $n$  is divisible by  $\#(R/I)^\times$ . But later

it will be convenient to suppress explicit mention of the required divisibility conditions.

## 2. First examples of order-dominant pairs: Proof of Theorem 1.1

Suppose that  $p$  is a prime with  $\left(\frac{A}{p}\right) = -1$  and that  $p$  divides  $A^n - B$  for some even positive integer  $n$ . Since  $B \equiv A^n \equiv (A^{n/2})^2 \pmod{p}$ , we see that

- $B$  is in the subgroup generated by  $A \pmod{p}$ , and
- $B$  is a square mod  $p$ .

Since  $A$  is not a square mod  $p$ , it cannot be that  $A$  is in the subgroup generated by  $B \pmod{p}$ . Hence,  $\langle B \pmod{p} \rangle \subsetneq \langle A \pmod{p} \rangle$ , and  $\text{ord}_p(A) > \text{ord}_p(B)$ . So to prove  $A, B$  is order-dominant, it suffices to produce infinitely many primes  $p$  of this kind.

Consider the situation where  $A, B$  are odd and positive with  $\left(\frac{-B(1-B)}{A}\right) = -1$ . Then  $A$  is coprime to both  $B$  and  $1 - B$ . We will locate primes  $p$  with  $\text{ord}_p(A) > \text{ord}_p(B)$  from among the prime divisors of

$$\frac{A^n - B}{B - 1},$$

for suitably chosen positive integers  $n$ . Loosely speaking, what we show is that as  $n$  gets more and more divisible, our procedure reveals larger and larger primes  $p$  with  $\text{ord}_p(A) > \text{ord}_p(B)$ . (Precisely: As  $n$  approaches 0 in  $\hat{\mathbb{Z}}$ , the discovered prime  $p$  approaches  $\infty$  in  $\bar{\mathbb{R}} = \mathbb{R} \cup \{\pm\infty\}$ .)

If  $n$  is sufficiently divisible, then  $\frac{A^n - B}{B - 1} = \frac{A^n - 1}{B - 1} - 1 \in \mathbb{Z}^+$ , and (since  $\gcd(A, 4(B - 1)) = 1$ ) in fact  $\frac{A^n - B}{B - 1} \equiv -1 \pmod{4}$ . By quadratic reciprocity (for the Jacobi symbol) and the first supplementary law,

$$\begin{aligned} \left(\frac{A}{(A^n - B)/(B - 1)}\right) &= (-1)^{(A-1)/2} \left(\frac{(A^n - B)/(B - 1)}{A}\right) \\ &= \left(\frac{-1}{A}\right) \left(\frac{-B(B - 1)}{A}\right) = \left(\frac{-B(1 - B)}{A}\right) = -1. \end{aligned}$$

Thus, we can choose  $p$  dividing  $\frac{A^n - B}{B - 1}$  with  $\left(\frac{A}{p}\right) = -1$ . Assuming that  $n$  is even (which holds whenever  $n$  is sufficiently divisible), we are in the situation described in the first paragraph of this section, and so  $\text{ord}_p(A) > \text{ord}_p(B)$ .

It remains to see that infinitely many distinct  $p$  arise in this construction. For that, it is enough to show that if  $p$  is a fixed prime and  $n$  is sufficiently divisible, then  $p$  does not divide  $\frac{A^n - B}{B - 1}$ . If  $p$  divides  $A$ , then  $p \nmid A^n - B$  for any  $n$ , and so  $p \nmid \frac{A^n - B}{B - 1}$ . So suppose  $p \nmid A$ . If  $n$  is sufficiently divisible,  $A^n \equiv 1 \pmod{p(B - 1)}$  and so  $\frac{A^n - B}{B - 1} \equiv -1 \pmod{p}$ . Hence,  $p \nmid \frac{A^n - B}{B - 1}$ .

Now suppose that  $A, B$  are odd and positive with  $(\frac{1-B}{A}) = -1$ . Again,  $A$  is coprime to  $B - 1$ . We look at primes dividing expressions of the form

$$\frac{BA^n - 1}{B - 1}.$$

If  $n$  is sufficiently divisible, then

$$\frac{BA^n - 1}{B - 1} \in \mathbb{Z}^+, \quad \text{with} \quad \frac{BA^n - 1}{B - 1} \equiv 1 \pmod{4}.$$

Moreover,

$$\left(\frac{A}{(BA^n - 1)/(B - 1)}\right) = \left(\frac{(BA^n - 1)/(B - 1)}{A}\right) = \left(\frac{1 - B}{A}\right) = -1.$$

Hence, there is a prime divisor  $p$  of  $(BA^n - 1)/(B - 1)$  with  $(\frac{A}{p}) = -1$ . Assuming  $n$  even,  $1/B \equiv A^n \equiv (A^{n/2})^2 \pmod{p}$ , and so (reasoning as in the first paragraph of this section)  $\langle 1/B \pmod{p} \rangle \subsetneq \langle A \pmod{p} \rangle$ . Hence,  $\text{ord}_p A > \text{ord}_p(1/B) = \text{ord}_p B$ . That infinitely many distinct  $p$  arise follows from the observation that for any fixed  $p$  not dividing  $A$ , and all  $n$  that are sufficiently divisible,  $\frac{BA^n - 1}{B - 1} \equiv \frac{B - 1}{B - 1} \equiv 1 \pmod{p}$ .

We turn now to (ii). To handle pairs  $2, B$  with  $B$  odd and positive, we look at  $p$  dividing

$$\frac{4 \cdot 2^n - B}{|4 - B|}.$$

Whenever  $n$  is sufficiently divisible,

$$\frac{4 \cdot 2^n - B}{|4 - B|} \in \mathbb{Z}^+, \quad \text{and} \quad \frac{4 \cdot 2^n - B}{|4 - B|} \equiv \pm 3 \pmod{8}.$$

Thus,  $(\frac{2}{(4 \cdot 2^n - B)/|4 - B|}) = -1$ . Choose  $p$  dividing  $\frac{4 \cdot 2^n - B}{|4 - B|}$  with  $(\frac{2}{p}) = -1$ . Then  $B \equiv 2^{n+2} \equiv (2^{(n/2+1)})^2 \pmod{p}$ , and so  $\langle B \pmod{p} \rangle \subsetneq \langle 2 \pmod{p} \rangle$ . Hence,  $\text{ord}_p(2) > \text{ord}_p(B)$ . Infinitely many distinct  $p$  arise this way since, for each fixed odd prime  $p$  and all  $n$  that are sufficiently divisible,  $\frac{4 \cdot 2^n - B}{|4 - B|} \equiv \frac{4 - B}{|4 - B|} \equiv \pm 1 \pmod{p}$ .

We breeze over the proof of (iii), concerning pairs  $A, 2$  with  $(\frac{-1}{A}) = -1$ , since the argument parallels the ones already described. This time one looks at primes dividing  $2A^n - 1$ , with  $n$  sufficiently divisible. If  $(\frac{-1}{A}) = 1$  but  $(\frac{-2}{A}) = -1$ , one considers prime divisors of  $A^n - 2$ , with  $n$  sufficiently divisible. We leave the details to the reader.

Finally we treat (iv). Let  $A, B$  be coprime integers larger than 1 with  $B > A^4$ . We look at primes dividing

$$\frac{A^{4+n} - B}{B - A^4}.$$

For each prime  $p$ ,

$$v_p\left(\frac{A^{4+n} - B}{B - A^4} + 1\right) = v_p(A^n - 1) + v_p(A^4) - v_p(B - A^4).$$

If  $p$  is fixed and  $n$  is sufficiently divisible, then the right-hand side is positive and in fact exceeds  $v_p(4A)$ : If  $p \mid A$ , this is clear, since  $v_p(B - A^4) = 0$  while  $v_p(A^4) > v_p(4A)$ . If  $p \nmid A$ , we use that  $v_p(A^n - 1)$  can be made arbitrarily large by making  $n$  sufficiently divisible. It follows that  $\frac{A^{4+n}-B}{B-A^4}$  is an integer for all sufficiently divisible  $n$  and that

$$\frac{A^{4+n} - B}{B - A^4} \equiv -1 \pmod{4A}.$$

Hence,  $\left(\frac{-4A}{(A^{4+n}-B)/(B-A^4)}\right) = \left(\frac{-4A}{-1}\right) = -1$ . (We have  $\left(\frac{-4A}{-1}\right) = -1$  since  $-4A$  is an example of a negative discriminant; one reference for this is [MoV07, §9.3].) Choose a prime  $p$  dividing  $\frac{A^{4+n}-B}{B-A^4}$  with  $\left(\frac{-4A}{p}\right) = -1$ . Since  $p \mid (-A)^{4+n} - B$  and  $-A$  is not a square mod  $p$ , a familiar argument shows that  $\text{ord}_p(-A) > \text{ord}_p(B)$ . Our above calculation with valuations implies that if  $p$  is fixed, then  $v_p\left(\frac{A^{4+n}-B}{B-A^4}\right) = 0$  for all sufficiently divisible  $n$ , and so this construction produces infinitely many different primes.

**Remarks 2.1.**

- (i) *A slight variant of the proof of Theorem 1.1(iv) establishes the following more general result. Let  $A, B$  be integers larger than 1. Let  $r_0$  be a nonnegative integer such that  $v_p(A^{r_0}) \geq v_p(B)$  for all primes  $p$  dividing  $A$ , and let  $r$  be an even integer with  $r > r_0 + 3$ . If  $B > A^r$ , then  $-A, B$  is order-dominant.*

*Using this result, it is straightforward to show that for each fixed  $A > 1$ , and almost all positive integers  $B$  (in the sense of asymptotic density), the pair  $-A, B$  is order-dominant.*

- (ii) *The cases discussed in Theorem 1.1 were chosen as representative of the basic method, but there are pairs of positive integers not covered by the conditions of Theorem 1.1 which can be shown order-dominant by this same strategy. One such pair is  $3, 7$  (look at primes dividing  $\frac{7 \cdot 3^n - 1}{2}$ ), and another is  $2, 6$  (look at primes dividing  $2^{n+1} - 3$ ).*

**3. Almost all pairs  $A, 2$  are order-dominant: Proof of Theorem 1.2**

The basic idea for the proof of Theorem 1.2 is encapsulated in the next lemma. Let  $F_n = 2^{2^n} + 1$  (for  $n = 0, 1, 2, 3, \dots$ ), the  $n$ th Fermat number. It is well-known that the  $F_n$  are pairwise relatively prime and that if  $p$  is a prime divisor of  $F_n$ , where  $n \geq 2$ , then  $\text{ord}_p(2) = 2^{n+1}$  and  $2^{n+2} \mid p - 1$  (see pages 5, 84 of [Rib96]).

**Lemma 3.1.** *Suppose  $A$  is a positive integer with the property that*

$$\left(\frac{A}{F_n}\right) = -1 \quad \text{for infinitely many positive integers } n.$$

*Then  $A, 2$  is order-dominant.*

**Proof.** Choose  $n \geq 2$  with  $\left(\frac{A}{F_n}\right) = -1$ . There is a prime  $p$  dividing  $F_n$  with  $\left(\frac{A}{p}\right) = -1$ , and for this prime,  $A^{(p-1)/2} \equiv -1 \pmod{p}$ . Hence,  $\text{ord}_p(A)$  divides  $p - 1$  but does not divide  $\frac{p-1}{2}$ , forcing  $v_2(\text{ord}_p(A)) = v_2(p - 1)$ . It follows that

$$\text{ord}_p(A) \geq 2^{v_2(p-1)} \geq 2^{n+2} > 2^{n+1} = \text{ord}_p(2).$$

Since  $p > \text{ord}_p(A) \geq 2^{n+2}$ , and  $n$  can be chosen arbitrarily large, there are infinitely many  $p$  with  $\text{ord}_p(A) > \text{ord}_p(2)$ .  $\square$

Primes  $A$  *failing* the hypothesis of Lemma 3.1 appear already in the literature; Müller [Mü07] calls these **anti-elite primes**. That is,  $A$  is anti-elite if  $\left(\frac{A}{F_n}\right) = 1$  for all large enough positive integers  $n$ . We will call any integer  $A$  satisfying this condition an **anti-elite integer**.

As Müller observed, trivial changes to the proof of Theorem 4 in [KLS02] show that anti-elite primes are sparse within the collection of all primes. Specifically, the count of anti-elite primes not exceeding  $x$  is  $O(x/(\log x)^{3/2})$ , for all  $x \geq 2$ .<sup>2</sup> In view of Lemma 3.1, to prove Theorem 1.2 it is enough to show that only  $o(x)$  positive integers  $A \leq x$  are anti-elite, as  $x \rightarrow \infty$ . We prove this in the following more precise form.

**Theorem 3.2.** *For each  $\epsilon > 0$  and all  $x > x_0(\epsilon)$ , the number of anti-elite  $A \in (1, x]$  is  $O_\epsilon(x/(\log x)^{1-\epsilon})$ .*

**Proof.** Write  $A = A_0A_1$ , where  $A_1$  is the largest odd divisor of  $A$ . We will assume that  $v_2(\lambda(A_1)) < T - 2$ , where

$$T := \left\lfloor \frac{\log(\log x / \log \log x)}{\log 2} \right\rfloor.$$

If  $v_2(\lambda(A_1)) \geq T - 2$ , then there is a prime  $p$  dividing  $A$  with  $p \equiv 1 \pmod{2^{T-2}}$ , and the number of such  $A \leq x$  is

$$\ll x \sum_{\substack{p \leq x \\ p \equiv 1 \pmod{2^{T-2}}}} \frac{1}{p} \ll x \frac{\log \log x}{2^{T-3}} \ll \frac{x(\log \log x)^2}{\log x},$$

which is  $O_\epsilon(x/(\log x)^{1-\epsilon})$ . Here the sum on  $p$  has been estimated by the Brun–Titchmarsh inequality [MoV07, Theorem 3.9, p. 90] and partial summation.

We fix a nonnegative integer  $t < T - 2$  and count the number of anti-elite  $A \in (1, x]$  with  $v_2(\lambda(A_1)) = t$ . For each such  $A$ , the sequence  $\left\{\left(\frac{A}{F_n}\right)\right\}_{n \geq t+2}$  is purely periodic. Indeed, if  $n \geq t+2$ , then  $n \geq 2$ , so that  $F_n \equiv 1 \pmod{8}$  and

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<sup>2</sup>A stronger upper bound of  $O(x/(\log x)^2)$  is claimed in [KLS02]. Just [Jus20] points out a small error in the proof and notes that, when corrected, 2 must be replaced by 3/2. In fact, one can recover an estimate almost as strong as originally claimed by a modification of the proof; see the end of our §3.

$\left(\frac{2}{F_n}\right) = 1$ . Hence,  $\left(\frac{A}{F_n}\right) = \left(\frac{A_1}{F_n}\right) = \left(\frac{F_n}{A_1}\right)$ , which depends only on  $F_n$  modulo  $A_1$ . In turn,  $F_n = 2^{2^n} + 1 \pmod{A_1}$  depends only on  $2^n$  modulo  $\lambda(A_1)$ . Write

$$\lambda(A_1) = 2^{v_2(\lambda(A_1))} B,$$

where  $B$  is odd. Since  $n \geq t = v_2(\lambda(A_1))$ , the residue class of  $2^n \pmod{\lambda(A_1)}$  is determined by  $2^n \pmod{B}$ , which depends only on  $n \pmod{\lambda(B)}$ . Collecting our results, we see that  $\left\{\left(\frac{A}{F_n}\right)\right\}_{n \geq t+2}$  is purely periodic (with period dividing  $\lambda(B)$ ).

Since  $A$  is anti-elite, it must be that each  $F_n$  with  $n \geq t + 2$  satisfies  $\left(\frac{A}{F_n}\right) = 1$ . In particular,

$$\left(\frac{A}{F_n}\right) = 1 \quad \text{for all } n \text{ with } t + 2 \leq n < T. \quad (2)$$

Factor  $A = ps$ , where  $p$  is prime,  $p \equiv 1 \pmod{2^t}$ . Our argument to bound the number of remaining  $A$  assumes two different forms according to the sizes of  $p$  and  $s$ .

Suppose first that  $s \leq \sqrt{x}$ , so that  $x/s \geq \sqrt{x}$ . It follows from (2) that  $p, s$  are prime to  $\prod_{t+2 \leq n < T} F_n$ , and that

$$\left(\frac{p}{F_n}\right) = \left(\frac{s}{F_n}\right) \quad \text{whenever } t + 2 \leq n < T. \quad (3)$$

We view  $s$  as fixed and count the number of corresponding  $p$ . Let  $F = \prod_{t+2 \leq n < T} F_n$ . Keeping in mind that  $p \equiv 1 \pmod{2^t}$ , we deduce from (3) that  $p$  belongs to one of  $\prod_{t+2 \leq n < T} \left(\frac{1}{2}\phi(F_n)\right) = 2^{t-T+2}\phi(F)$  coprime residue classes modulo  $2^t F$ . (We use here that each symbol  $\left(\frac{\cdot}{F_n}\right)$  is a nontrivial quadratic character mod  $F_n$ , since  $F_n$  is not a square.) Notice that

$$F < \prod_{n=0}^{T-1} F_n = F_T - 2 < F_T.$$

So by our choice of  $T$ , and the inequality  $t < T - 2$ , we have  $2^t F < 2^t F_T = x^{o(1)}$  (as  $x \rightarrow \infty$ ). Since  $p = A/s \leq x/s$ , the Brun–Titchmarsh inequality tells us that the number of possibilities for  $p$  is  $O(2^{-T} \frac{x}{s \log x})$ . Summing on  $s \leq \sqrt{x}$  shows that the number of possible  $A$  in this case is

$$\ll \frac{x}{2^T} \ll \frac{x \log \log x}{\log x}.$$

Now suppose that  $s > \sqrt{x}$ . Then  $p \leq x/s < \sqrt{x}$ . From (2), we have with  $m = A$  that

$$\frac{1}{2^{T-t-2}} \prod_{t+2 \leq n < T} \left(1 + \left(\frac{m}{F_n}\right)\right) = 1.$$

Since the above left-hand side is nonnegative for every  $m$ , we conclude that an upper bound for the count of remaining  $A$  is

$$\frac{1}{2^{T-t-2}} \sum_{\substack{p \leq \sqrt{x} \\ p \equiv 1 \pmod{2^t}}} \sum_{s \leq x/p} \prod_{t+2 \leq n < T} \left( 1 + \left( \frac{sp}{F_n} \right) \right).$$

Expanding the product and bringing the sums on  $s, p$  inside gives a main term of size

$$\begin{aligned} \frac{1}{2^{T-t-2}} \sum_{\substack{p \leq \sqrt{x} \\ p \equiv 1 \pmod{2^t}}} \sum_{s \leq x/p} 1 &\ll \frac{1}{2^{T-t}} x \sum_{\substack{p \leq \sqrt{x} \\ p \equiv 1 \pmod{2^t}}} \frac{1}{p} \\ &\ll \frac{x \log \log x}{2^T} \ll \frac{x(\log \log x)^2}{\log x}. \end{aligned}$$

There are also  $2^{T-t-2} - 1$  error terms of the form  $\frac{1}{2^{T-t-2}} \sum_{p,s} \left( \frac{ps}{D} \right)$ , where  $D$  is the product of some nonempty subset of  $\{F_{t+2}, F_{t+3}, \dots, F_{T-1}\}$ . Since Fermat numbers are pairwise coprime,  $D$  is not a square, and  $\left( \frac{\cdot}{D} \right)$  is a nontrivial Dirichlet character modulo  $D$ . Moreover,  $D \leq F = x^{o(1)}$ . Using the trivial bound of  $D$  for a nontrivial character sum mod  $D$ , we see that

$$\begin{aligned} \sum_{\substack{p \leq \sqrt{x} \\ p \equiv 1 \pmod{2^t}}} \sum_{s \leq x/p} \left( \frac{ps}{D} \right) &= \sum_{\substack{p \leq \sqrt{x} \\ p \equiv 1 \pmod{2^t}}} \left( \frac{p}{D} \right) \sum_{s \leq x/p} \left( \frac{s}{D} \right) \\ &\ll D \sum_{\substack{p \leq \sqrt{x} \\ p \equiv 1 \pmod{2^t}}} 1 \ll Dx^{1/2}. \end{aligned}$$

Hence, the errors contribute  $\ll Dx^{1/2} \ll x^{2/3}$ . This is negligible compared to our main term, and so the number of  $A$  that arise in this second case is  $O(x(\log \log x)^2 / \log x)$ .

Assembling our results, we have proved that for each  $t$ , the number of corresponding  $A$  is  $O(x(\log \log x)^2 / \log x)$ . It remains to sum on  $t$ . But there are only  $O(\log \log x)$  possible values of  $t$ , and so the total number of anti-elite  $A \leq x$  is  $O(x(\log \log x)^3 / \log x)$ , which is  $O_\epsilon(x / (\log x)^{1-\epsilon})$ .  $\square$

**Remark 3.3.** *The anti-elite numbers up to 150 are*

- 1, **2**, 4, 8, 9, **13**, 15, 16, **17**, 18, 21, 25, 26, 30, 32, 34, 35, 36, 42, 49, 50, 52, 60, 64, 68, 70, 72, 81, 84, **97**, 98, 100, 104, 117, 120, 121, 123, 128, 135, 136, 140, 144.

*Anti-elite primes are shown in bold.*

The proof of Theorem 3.2 is a more careful variant of the proof of Theorem 4 in [KLS02], the primary difference being that we keep track of the exact value of  $t$  (the original argument only tracked whether  $t$  was small or large, in a certain sense). Inserting this idea back into [KLS02] will show that the count of elite primes up to  $x$  is  $O_\epsilon(x / (\log x)^{2-\epsilon})$ , essentially recovering the

bound of  $O(x/(\log x)^2)$  claimed in [KLS02]. Under GRH, the first author showed in [Jus20] that the count of elite primes up to  $x$  is  $O_\epsilon(x^{5/6+\epsilon})$ ; the present method allows us to replace  $5/6$  by  $3/4$ .

#### 4. Order-dominant pairs $A, -3$ and $A, 3$ : Proof of

##### Theorem 1.3

Let  $\zeta = e^{2\pi i/3} = \frac{-1+\sqrt{-3}}{2}$ . Below, we work in the ring  $\mathbb{Z}[\zeta] = \mathcal{O}_K$ , where  $K = \mathbb{Q}(\zeta)$ . Let  $\lambda = 1 - \zeta$ , so that  $\lambda^2 = -3\zeta$  and the ideal  $(\lambda^2) = (3)$ .

Take first the case when  $A$  is even. Thinking of  $n$  as sufficiently divisible (and in particular, even), we set

$$\beta := A^{n/2} - \sqrt{-3}$$

and we attempt to evaluate the cubic residue symbol  $\left(\frac{A}{\beta}\right)_3$ . Since  $\sqrt{-3} = 2\zeta + 1$ , we have

$$\beta = A^{n/2} - 1 - 2\zeta. \quad (4)$$

Since  $3 \nmid A$ , for sufficiently divisible  $n$  we find that  $A^{n/2} \equiv 1 \pmod{3}$ , so that

$$\beta \equiv -2\zeta \pmod{\lambda^2}.$$

Hence,  $\zeta^2\beta$  is congruent, modulo  $\lambda^2$ , to a rational integer coprime to 3; that is,  $\zeta^2\beta$  is **primary** in the sense required for an application of Eisenstein's  $\ell$ th power reciprocity law with  $\ell = 3$  (see, e.g., pp. 206–207 of [IR90]). By that law, we deduce that (for sufficiently divisible  $n$ )

$$\left(\frac{A}{\beta}\right)_3 = \left(\frac{A}{\zeta^2\beta}\right)_3 = \left(\frac{\zeta^2\beta}{A}\right)_3 = \left(\frac{-\zeta^2\sqrt{-3}}{A}\right)_3,$$

so that

$$\left(\frac{A}{\beta}\right)_3^2 = \left(\frac{-3\zeta}{A}\right)_3 = \left(\frac{\lambda^2}{A}\right)_3 = \left(\frac{\lambda}{A}\right)_3^2,$$

forcing  $\left(\frac{A}{\beta}\right)_3 = \left(\frac{\lambda}{A}\right)_3$ , since  $\left(\frac{A}{\beta}\right)_3$  and  $\left(\frac{\lambda}{A}\right)_3$  are third roots of unity. From the supplementary laws for Eisenstein reciprocity (see p. 365 of [Lem00]),

$$\left(\frac{\lambda}{A}\right)_3 = \left(\frac{\zeta}{A}\right)_3^{\frac{1}{2}(3-1)} = \left(\frac{\zeta}{A}\right)_3 = \zeta^{(A^2-1)/3}.$$

Since  $A^2 \not\equiv 1 \pmod{9}$ , the exponent on  $\zeta$  is not a multiple of 3. Thus,  $\left(\frac{A}{\beta}\right)_3 \neq 1$ . In particular,  $A$  is not a cube modulo  $\beta$ , in  $\mathbb{Z}[\zeta]$ .

Since  $A$  is even, we see from (4) that when  $\beta$  is written as a  $\mathbb{Z}$ -linear combination of  $1, \zeta$ , the coefficient of  $1$  and the coefficient of  $\zeta$  are relatively prime. For any  $\beta$  of this kind, a straightforward calculation shows that the canonical map  $\mathbb{Z} \rightarrow \mathbb{Z}[\zeta]/(\beta)$  is surjective, and so induces an isomorphism  $\mathbb{Z}/(N\beta) \cong \mathbb{Z}[\zeta]/(\beta)$ . Thus, the calculation of the last paragraph implies that  $A$  is not a cube modulo  $N\beta = A^n + 3$ , in  $\mathbb{Z}$ . If  $A$  were a cube modulo every prime factor of  $A^n + 3$ , then  $A$  would be a cube modulo  $A^n + 3$ , by

Hensel’s lemma and the Chinese remainder theorem. (We use here that  $A$  is prime to  $A^n + 3$ , and that  $3 \nmid A^n + 3$ .) So we can choose a prime  $p$  dividing  $A^n + 3$  with  $A$  not a cube modulo  $p$ .

If  $n$  is sufficiently divisible, then  $3 \mid n$ . Then  $A^n \equiv -3 \pmod{p}$  implies that  $-3$  is a cube modulo  $p$  and that  $-3 \pmod{p}$  belongs to the subgroup generated by  $A \pmod{p}$ . Since  $A$  is not a cube mod  $p$ , we see  $A$  is not in the subgroup generated by  $-3$ , and thus  $\langle -3 \pmod{p} \rangle \subsetneq \langle A \pmod{p} \rangle$ . It follows that  $\text{ord}_p(A)/\text{ord}_p(-3)$  is an integer larger than 1. To see that this integer is a multiple of 3, notice that  $p \equiv 1 \pmod{3}$  (otherwise,  $A$  would be a cube mod  $p$ ), that  $v_3(\text{ord}_p(A)) = v_3(p - 1)$  (since  $A$  is not a cube) and that  $v_3(\text{ord}_p(-3)) < v_3(p - 1)$  (since  $-3$  is a cube). Thus,  $v_3(\text{ord}_p(A)/\text{ord}_p(-3)) \geq 1$ .

We have shown so far that if  $n$  is sufficiently divisible, one can find a prime factor of  $A^n + 3$  with  $\text{ord}_p(A)/\text{ord}_p(3)$  an integer multiple of 3. To see that infinitely many distinct primes arise, notice that all of the  $p$  produced by this construction are odd and coprime to  $A$ . Then observe that if  $p$  is any fixed prime not dividing  $2A$ , then  $A^n + 3 \equiv 4 \not\equiv 0 \pmod{p}$  whenever  $n$  is sufficiently divisible.

The proof is essentially the same when  $A$  is odd, except that now one should set  $\beta := \frac{1}{2}(A^{n/2} - \sqrt{-3})$ . It is also useful to observe that  $\left(\frac{2}{A}\right)_3 = \left(\frac{A}{2}\right)_3 = \left(\frac{1}{2}\right)_3 = 1$ . We leave the details to the reader.

### 5. Equal orders in imaginary quadratic rings: Proof of

#### Theorem 1.4

Let  $K$  be a quadratic field of discriminant  $\Delta < 0$ , and let  $\alpha, \beta$  be distinct nonzero elements of  $\mathcal{O}_K$ , neither of which is a root of unity. Let  $I$  be the largest ideal divisor of  $(\beta - \alpha)$  coprime to  $(\alpha)$ . The prime ideals  $P$  referred to in the conclusion of Theorem 1.4 will come to us as divisors of the (ideal) expression

$$(\beta\alpha^\ell - 1)/I,$$

where  $\ell$  is a prime number for which  $\ell + 1$  is sufficiently divisible. It is important to note that any “sufficiently divisible” hypothesis on  $\ell + 1$  is always satisfied by infinitely many primes  $\ell$ ; this follows, e.g., from Dirichlet’s theorem on primes in progressions. (For an elementary proof of the  $-1 \pmod{M}$  case of Dirichlet’s theorem used here, see §50 of [Nag51].)

If  $\ell + 1$  is sufficiently divisible, then  $\alpha^{\ell+1} \equiv 1 \pmod{I}$ , so that  $\alpha(\beta\alpha^\ell - 1) \equiv \beta - \alpha \equiv 0 \pmod{I}$ . Hence,  $(\beta\alpha^\ell - 1)/I$  is a nonzero, integral ideal of  $\mathcal{O}_K$ . Since  $\Delta \mid \ell + 1$  when  $\ell + 1$  is sufficiently divisible,

$$\sqrt{\Delta}^\ell \equiv \Delta^{(\ell-1)/2} \sqrt{\Delta} \equiv \left(\frac{\Delta}{\ell}\right) \sqrt{\Delta} \equiv \left(\frac{\Delta}{-1}\right) \sqrt{\Delta} \equiv -\sqrt{\Delta} \pmod{\ell}.$$

So using a bar for complex conjugation (identified with the nontrivial automorphism of  $K$ ),  $\alpha^\ell \equiv \bar{\alpha} \pmod{\ell}$ , and

$$\begin{aligned} N((\beta\alpha^\ell - 1)/I) &= N(\beta\alpha^\ell - 1)/N(I) \\ &\equiv N(\beta\bar{\alpha} - 1)/N(I) \pmod{\ell}. \end{aligned}$$

In the last line, division by  $N(I) \pmod{\ell}$  is to be understood as multiplication by the inverse of  $N(I) \pmod{\ell}$ . The rational number  $N(\beta\bar{\alpha} - 1)/N(I)$  exceeds 1, since

$$\begin{aligned} N(\beta\bar{\alpha} - 1) - N(I) &\geq N(\beta\bar{\alpha} - 1) - N(\beta - \alpha) \\ &= (\beta\bar{\alpha} - 1)(\bar{\beta}\alpha - 1) - (\beta - \alpha)(\bar{\beta} - \bar{\alpha}) \\ &= (\beta\bar{\beta} - 1)(\alpha\bar{\alpha} - 1) = (N\alpha - 1)(N\beta - 1) > 0. \end{aligned}$$

It follows that if  $\ell + 1$  is sufficiently divisible,

$$N(\beta\bar{\alpha} - 1)/N(I) \not\equiv 1 \pmod{\ell}.$$

Thus, there must be a prime ideal  $P$  of  $\mathcal{O}_K$  dividing  $(\beta\alpha^\ell - 1)/I$  with  $N(P) \not\equiv 1 \pmod{\ell}$ , i.e., with  $\ell \nmid (\mathcal{O}_K/P)^\times$ . Since  $\beta\alpha^\ell \equiv 1 \pmod{P}$ , we deduce that  $\langle \beta \pmod{P} \rangle = \langle \alpha^{-\ell} \pmod{P} \rangle = \langle \alpha \pmod{P} \rangle$ .

To show that infinitely many such  $P$  arise, we show that any fixed  $P$  is coprime to  $(\beta\alpha^\ell - 1)/I$  for all  $\ell$  with  $\ell + 1$  sufficiently divisible. This is clear if  $P \mid (\alpha)$ . Otherwise, choose  $k$  for which  $P^k \parallel (\beta - \alpha)$ . Then  $P^k \parallel I$ . Whenever  $\ell + 1$  is sufficiently divisible,

$$\alpha(\beta\alpha^\ell - 1) \equiv (\beta - \alpha) \pmod{P^{k+1}},$$

which implies that  $P^k \parallel (\beta\alpha^\ell - 1)$ . But then  $P \nmid (\beta\alpha^\ell - 1)/I$ .

**Remark 5.1.** *It would seem interesting to consider the problems of this paper for other algebraic groups. For instance, fix an elliptic curve  $E$  over  $\mathbb{Q}$  of positive rank, and suppose that  $P, Q \in E(\mathbb{Q})$  are points of infinite order. Under what conditions on  $P, Q$  are there infinitely many primes  $p$  (a) for which  $P$  and  $Q$  have the same order in  $E(\mathbb{F}_p)$ ? (b) for which the order of  $P$  in  $E(\mathbb{F}_p)$  is larger than the order of  $Q$ ?*

## Acknowledgements

The first author (M.J.) was supported by the UGA Algebraic Geometry, Algebra, and Number Theory RTG grant, NSF award DMS-1344994. The second author (P.P.) was supported by NSF award DMS-2001581. We thank Michael Filaseta, Pieter Moree, Carl Pomerance, Enrique Treviño, and the referee for helpful comments. We are also grateful to MathOverflow user [Hhhhhhhhhhh](#) for the post which brought this question to our attention [[Hhh20](#)].

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