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INTEGER PARTS OF POWERS OF QUADRATIC UNITS

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ABSTRACT. Let $\alpha > 1$ be a unit in a quadratic field. The integer part of α^n, denoted $[\alpha^n]$, is shown to be composite infinitely often. Provided $\alpha \neq (1+\sqrt{5})/2$, it is shown that the number of primes among $[\alpha], [\alpha^2], \dots, [\alpha^n]$ is bounded by a function asymptotic to $c \cdot \log^2 n$, with $c = 1/(2\log 2 \cdot \log 3)$.

Let $\alpha > 1$ be a unit in a quadratic field $Q(\sqrt{D})$, with $D > 1$ a square-free rational integer. It is known in some cases that the integer parts $[\alpha^n]$ of powers of α ($n = 1, 2, 3, \dots$) are composite infinitely often [**1**]. We show this in general, the proof guaranteeing in fact that infinitely many of the $[\alpha^n]$ are divisible by $[\alpha]$. (There is one exceptional case $\alpha = (1+\sqrt{5})/2$ wherein $[\alpha] = 1$; here infinitely many of the $[\alpha^n]$ are divisible by $[\alpha^2] > 1$.)

Define $f_\alpha(x)$ to mean the number of n, $1 \leq n \leq x$, for which $[\alpha^n]$ happens to be prime. We derive a bound on $f_\alpha(x)$ which is independent of both α and $Q(\sqrt{D})$ (except that we require $\alpha \neq (1+\sqrt{5})/2$), namely

$$f_\alpha(x) \leq 1 + B(x),$$

where $B(x)$ denotes here, and in what follows, the number of positive integers $\leq x$ of the form $2^r 3^s$, $r \geq 0$, $s \geq 0$.

HEURISTIC REMARK. As $x \to \infty$ the function $1 + B(x)$ is asymptotic to $c\log^2 x$, where $c = 1/(2 \cdot \log 2 \cdot \log 3)$. If one says "$m$ is prime with probability $1/\log m$," then $[\alpha^n]$ is prime with probability about $1/n \log \alpha$. Summing this for $n \leq x$ we expect $\sim (1/\log \alpha) \log x$ primes in the sequence $[\alpha^n]$, $1 \leq n \leq x$. The latter function grows more slowly than $c \log^2 x$, so in this sense the bound $1 + B(x)$ is not at odds with probability.

We show first that for α with norm $N(\alpha) = -1$, $[\alpha]$ divides $[\alpha^n]$ for all odd n. This reduces us to the norm 1 case, in which we show that, if $[\alpha^n]$ is prime, then n is of the form $2^r 3^s$ (giving the above bound).

LEMMA 1. *Suppose $\alpha > 1$ is a unit of $Q(\sqrt{D})$ with $D > 1$ squarefree. Write t_n for $[\alpha^n]$, and let $N(\beta)$ denote the norm and β' the conjugate of β for β any integer of $Q(\sqrt{D})$. Then:*

(a) *If $N(\alpha) = 1$, then $t_n = (\alpha^n + \alpha^{-n}) - 1$.*

(b) *If $N(\alpha) = -1$, then*

$$t_n = \begin{cases} \alpha^n - \alpha^{-n}, & \text{if } n \text{ is odd}, \\ (\alpha^n + \alpha^{-n}) - 1, & \text{if } n \text{ is even}. \end{cases}$$

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PROOF. $N(\alpha) = 1$ means $\alpha\alpha' = 1$, so $\alpha' = \alpha^{-1}$. Write α^n in the form $(a_n + b_n\sqrt{D})/2$; then a_n and b_n are rational integers, and we have $a_n = \alpha^n + \alpha'^n = \alpha^n + \alpha^{-n}$, so that $\alpha^n = a_n - \alpha^{-n}$. Since $0 < \alpha^{-n} < 1$, part (a) follows.

Now assume $N(\alpha) = -1$. Then $\alpha\alpha' = -1$ so $\alpha' = -\alpha^{-1}$. Then $a_n = \alpha^n + \alpha'^n = \alpha^n + (-\alpha^{-1})^n = \alpha^n + (-1)^n\alpha^{-n}$. If n is odd, then from $a_n = \alpha^n - \alpha^{-n}$ we have $\alpha^n = a_n + \alpha^{-n}$, and since $0 < \alpha^{-n} < 1$, $t_n = [\alpha^n] = a_n = \alpha^n - \alpha^{-n}$.

If n is even, then from $a_n = \alpha^n + \alpha^{-n}$ we conclude as in case (a) that $t_n = \alpha^n + \alpha^{-n} - 1$. □

LEMMA 2. *Suppose $N(\alpha) = -1$ and set $t_n = [\alpha^n]$. Then whenever $m \geq n$ we have the four following multiplication formulas for $t_m t_n$, depending on the parity of m and n:*

(a) *m odd, n odd: $t_m t_n = t_{m+n} - t_{m-n}$,*

(b) *m even, n odd: $t_m t_n = t_{m+n} - t_{m-n} - t_n$,*

(c) *m odd, n even: $t_m t_n = t_{m+n} + t_{m-n} - t_m$,*

(d) *m even, n even: $t_m t_n = t_{m+n} + t_{m-n} - t_m - t_n + 1$.*

Furthermore, in the case $N(\alpha) = +1$, formula (d) *holds* (*without the parity restriction*) *for any m, n with $m \geq n$. In all the formulas t_0 is allowed and is* 1.

PROOF. Substitute for t_m and t_n their expressions from Lemma 1; the formulas follow (after some algebra).

LEMMA 3. *Suppose $N(\alpha) = -1$ and $t_n = [\alpha^n]$. Then we have the congruences* (*to the modulus t_1*):

$$t_n \equiv \begin{cases} +1, & n \text{ even}, \\ 0, & n \text{ odd}. \end{cases}$$

PROOF. We have $t_0 \equiv 1$, $t_1 \equiv 0$. Apply Lemma 2 with $n = 1$. Then we only use formulas (a) and (b), and to the modulus t_1 they both read

$$0 \equiv t_{m+1} - t_{m-1}.$$

Therefore $t_2 \equiv t_0 \equiv 1$, $t_3 \equiv t_1 \equiv 0$, and so on.

Note that (except when $\alpha = (1+\sqrt{5})/2$, when $t_1 = 1$), on considering when $[\alpha^n]$ is composite where $N(\alpha) = -1$, the preceding lemma allows us to consider only $[\alpha^2], [\alpha^4], \dots$, i.e. the sequence $[\beta^n] = [\alpha^{2n}]$, where $\beta = \alpha^2$ has norm $+1$. That $\alpha = (1+\sqrt{5})/2$ is the only quadratic unit for which $t_1 = [\alpha] = 1$ follows easily from $4N(\alpha) = a^2 - Db^2$.

LEMMA 4. *Suppose $N(\beta) = +1$ ($\beta > 1$) and $t_n = [\beta^n]$. Then we have the congruences in the following table, to the modulus t_1:*

$n \pmod 6$	0	1	2	3	4	5
$t_n \pmod{t_1}$	1	0	-2	-3	-2	0

PROOF. In formula (d) of Lemma 2 (which applies here in all cases $m \geq n$) put $n = 1$; to the modulus t_1 the formula reads

$$0 \equiv t_{m+1} + t_{m-1} - t_m + 1,$$

which gives the $t_m \pmod{t_1}$ recursively, producing the above table. □

COROLLARY. *Regardless of* $N(\alpha)$, $[\alpha]$ *divides* $[\alpha^n]$ *infinitely often. If* $\alpha \neq (1+\sqrt{5})/2$, *this* $[\alpha]$ *is* > 1.

LEMMA 5. *Suppose* $N(\gamma) = +1$ $(\gamma > 1)$ *and set* $t_n = [\gamma^n]$. *Then if* t_n *is prime,* n *is of the form* $2^r 3^s$.

PROOF. First note that $t_1 > 1$ since $N(\gamma) = +1$ precludes $\gamma = (1+\sqrt{5})/2$. It follows that $t_h > 1$ for $h \geq 1$.

Suppose n is not of the form $2^r 3^s$. Then n has a factor $6k+5$ or $6k+7$ with $k \geq 0$. Write $n = h(6k+5)$ or $n = h(6k+7)$, with $h \geq 1$. Then Lemma 4 with $\beta = \gamma^h$ shows that t_n is divisible by t_h, and $1 < t_h < t_n$ so that t_n is composite. □

COROLLARY. *If* $N(\gamma) = +1$ *and* $f_\gamma(x)$ *denotes the number of primes among* $t_1, t_2, \ldots, t_n$ *with* $n = [x]$, *then* $f_\gamma(x) \leq B(x)$.

THEOREM 1. *Suppose* $\alpha > 1$ $(\alpha \neq (1+\sqrt{5})/2)$ *is a unit in some quadratic field* $Q(\sqrt{D})$, $D > 1$ *squarefree. With* $f_\alpha(x)$ *as above, then*

$$f_\alpha(x) \leq 1 + B(x).$$

This bound is independent of α *and* $Q(\sqrt{D})$.

PROOF. First suppose $N(\alpha) = -1$. Since $\alpha \neq (1+\sqrt{5})/2$, $[\alpha] > 1$ and Lemma 3 imply that $[\alpha^n]$ is composite if n is odd and ≥ 3. $f_\alpha(x)$ is then at most $1+e$, where e is the number of primes among $[\alpha^2], [\alpha^4], \ldots, [\alpha^{n'}]$ (where n' is either n or $n-1$). By Corollary to Lemma 5 with $\gamma = \alpha^2$, the latter number is at most $B(x/2) \leq B(x)$; the bound holds.

When $N(\alpha) = +1$, Corollary to Lemma 5 already gives the bound. □

REMARK. Let $\alpha = (1+\sqrt{5})/2$. If n is odd and composite, say $n = n_1 n_2$ with n_1, n_2 odd and ≥ 3, then $[\alpha^{n_1}] > 1$ and Lemma 3 shows that $[\alpha^n]$ is divisible by $[\alpha^{n_1}]$. Hence among the odd powers only $[\alpha^p]$ (with p an odd prime) can be primes.

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