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THE GREATEST SQUARE FREE FACTOR OF A BINARY RECURSIVE SEQUENCE

By T. N. SHOREY

§ 1. For any sequence of integers $u_0, u_1, \dots, u_m, \dots$ satisfying

$$u_m = r u_{m-1} + s u_{m-2}, \quad m = 2, 3, \dots$$

where r and s are rational integers with $r^2 + 4s \neq 0$, we have

$$(1) \quad u_m = a \alpha^m + b \beta^m, \quad m = 0, 1, 2, \dots$$

where α and β are roots of the polynomial $X^2 - rX - s$ and

$$(2) \quad a = \frac{u_0 \beta - u_1}{\beta - \alpha}, \quad b = \frac{u_1 - u_0 \alpha}{\beta - \alpha}.$$

The polynomial $X^2 - rX - s$ is called the polynomial associated to the sequence $\{u_m\}$. The sequence $\{u_m\}$ is said to be a non-degenerate binary recursive sequence if a, b, α, β are non-zero and α/β is not a root of unity. For a rational integer κ with $|\kappa| > 1$, denote by $P(\kappa)$ the greatest prime factor of κ and by $Q(\kappa)$ the greatest square free factor of κ . If p_1, \dots, p_r are all the distinct primes dividing κ , then $Q(\kappa) = p_1 \dots p_r$. For non-zero rational integers x and y , denote by $[x, y]$ and (x, y) , respectively, the least common multiple and the greatest common divisor of x and y . Further we define $P(1) = P(-1) = 1$ and

$$P\left(\frac{x}{y}\right) = P\left(\frac{\kappa}{(x, y)} \frac{y}{(\kappa, y)}\right) = P\left(\frac{[x, y]}{(x, y)}\right)$$

and

$$Q\left(\frac{x}{y}\right) = Q\left(\frac{[x, y]}{(x, y)}\right)$$

Let $\{u_m\}$ be a non-degenerate binary recursive sequence given by (1). Stewart [4] proved that

$$Q(u_m) > C \left(\frac{m}{((\log m)^2)} \right)^{1/d}, m > C',$$

where $d = [Q(\alpha) : Q]$ and $C > 0, C' > 0$ are effectively computable numbers depending only on a and b . Observe that $d = 1$ or 2 . Further, if $|\alpha| > |\beta|$, Stewart [4] proved that for any θ with $0 < \theta < 1$,

$$Q(u_m) > m^\theta, m > C'',$$

where $C'' > 0$ is an effectively computable number depending only on θ and the sequence $\{u_m\}$. We shall generalise and strengthen this result as follows:

Theorem 1

Let $\{u_m\}$ be a non-degenerate binary recursive sequence. There exist effectively computable numbers $C_1 > 0$ and $C_2 > 0$ depending only on the sequence $\{u_m\}$ such that for every $m > C_1$, we have

$$\log Q(u_m) > C_2 (\log m)^2 (\log \log m)^{-1}.$$

The improvement depends on utilising the fact that the contribution from small primes in u_m is small. Stewart [5] proved theorem 1 for the greatest square free factor of the members of Lucas and Lehmer sequences. Further, for Lucas and Lehmer sequences, Stewart [5] proved that for almost all m

$$\log Q(u_m) > (\log m)^{2+\log 2-\epsilon}, \epsilon > 0.$$

Theorem 1 is contained in the following result.

Theorem 2

Let $\{u_m\}$ be a non-degenerate binary recursive sequence. There exist effectively computable numbers $C_3 > 0$ and $C_4 > 0$ depending only on the sequence $\{u_m\}$ such that for every pair m, n with $m > n$, $m \geq C_3$ and $u_n \neq 0$, we have

$$\log Q(\Delta'_{m, n}) > C_4 (\log m)^2 (\log \log m)^{-1}$$

where

$$\Delta'_{m, n} = [u_m, u_n] / (u_m, u_n).$$

For a non-degenerate binary recursive sequence $\{u_m\}$, observe that the equation $u_m = 0$ implies that m is bounded by an effectively computable number depending only on the sequence $\{u_m\}$. We apply theorem 2 with the least integer n (n is either 0 or 1) such that $u_n \neq 0$ to obtain theorem 1. For estimates on $P(u_m)$ and $P(\Delta'_{m, n})$, we refer to Stewart [4] and the author [3]. See also the next theorem.

Let $\{u_m\}$ and $\{v_m\}$ be non-degenerate binary recursive sequences whose associated polynomials are identically equal. Denote by α and β the roots of their associated polynomial. Then the sequence $\{u_m\}$ is given by (1) and (2). Further for $m = 0, 1, 2, \dots$, we have

$$v_m = a_1 \alpha^m + b_1 \beta^m$$

where

$$a_1 = \frac{v_0 \beta - v_1}{\beta - \alpha}, \quad b_1 = \frac{v_1 - v_0 \alpha}{\beta - \alpha}.$$

For m and n with $u_m v_n \neq 0$, put

$$\Delta_{m,n} = [u_m, v_n] / (u_m v_n)$$

Then theorem 2 is a particular case of the following result.

Theorem 3

Let $A > 0$ and $0 < K < (d+1)^{-1}$ where $d = [Q(\alpha) : Q]$. There exist effectively computable numbers $C_5 > 0$ and $C_6 > 0$ depending only on A, K , the sequences $\{u_m\}$ and $\{v_m\}$ such that for every pair m, n with $m > n, m \geq C_5, v_n \neq 0$ and

$$(3) \quad \frac{a \alpha^m}{a_1 \alpha^n} \neq \frac{b \beta^m}{b_1 \beta^n},$$

either

$$\log P(\Delta_{m,n}) > (\log m)^A$$

or

$$\sum_{\substack{p \mid \Delta_{m,n} \\ p > m^K}} 1 > C_6 \frac{\log m}{\log \log m}$$

where p runs through primes

For the proof of theorem 2, we may assume $\log P(\Delta'_{m,n}) < (\log m)^2$. Then we apply theorem 3 with $\{u_m\} = \{v_m\}$, $A = 2$ and $K = \frac{1}{4}$. Observe that (3) is satisfied, since α/β is not a root of unity. Now the assertion of theorem 2 follows immediately.

The proof of theorem 3 depends on the theory of linear forms in logarithms. Let $\alpha_1, \dots, \alpha_n$ be non-zero algebraic numbers. Let K be their splitting field over Q . Put $D = [K:Q]$

We denote by A_1, \dots, A_n upper bounds for the heights of $\alpha_1, \dots, \alpha_n$ respectively, where we assume that $A_j > 3$ for $1 < j < n$. Write

$$\Omega' = \prod_{j=1}^{n-1} \log A_j, \quad \Omega = \Omega' \log A_n.$$

The proof of theorem 3 depends on the following theorem of Baker [1] on linear forms in logarithms.

Theorem A.

There exist effectively computable absolute constants $C_7 > 0$ and $C_8 > 0$ such that the inequalities

$$0 < \left| \alpha_1^{b_1} \dots \alpha_n^{b_n} - 1 \right| < \exp \left(- (C_7 n D)^{C_8 n} \Omega \log \Omega' \log B \right)$$

have no solution in rational integers b_1, \dots, b_n with absolute values at most $B (> 2)$.

We shall also need a p -adic analogue, due to van der Poorten [2], of theorem A.

Theorem B.

Let \mathfrak{p} be a prime ideal of K lying above a rational prime p . There exist effectively computable absolute constants $C_9 > 0$ and $C_{10} > 0$ such that the inequalities

$$\infty > \text{ord}_{\mathfrak{p}} \left(\alpha_1^{b_1} \dots \alpha_n^{b_n} - 1 \right) > (C_9 n D)^{C_{10} n} \frac{p^D}{\log p} \Omega (\log B)^2$$

have no solution in rational integers b_1, \dots, b_n with absolute values at most $B (> 2)$.

§ 2. Proof of theorem 3.

Let $A > 0$ and $0 < K < (d+1)^{-1}$. Put

$$(4) \quad \tau = K(d+1).$$

Observe that $0 < \tau < 1$. Let $\{u_m\}$ and $\{v_m\}$ be as in theorem 3. There is no loss of generality in assuming that $|\alpha| \geq |\beta|$. Then, since α/β is not a root of unity, we find that $|\alpha| > 1$. For algebraic integer $\kappa \in Q(\alpha)$, denote by $[\kappa]$ the ideal generated by κ in the ring of integers of $Q(\alpha)$. There exists a positive rational integer k such that

$$([\alpha^2], [\beta^2]) = [k].$$

Put $\alpha_1 = \alpha^2/k$ and $\beta_1 = \beta^2/k$. Then the ideals $[\alpha_1]$ and $[\beta_1]$ are relatively coprime. For $m = 0, 1, 2, \dots$, notice that

$$U_m = k^{-m} u_{2m} = a\alpha_1^m + b\beta_1^m,$$

$$U'_m = k^{-m} u_{2m+1} = a\alpha\alpha_1^m + b\beta\beta_1^m,$$

$$V_m = k^{-m} v_{2m} = a_1\alpha_1^m + b_1\beta_1^m,$$

$$V'_m = k^{-m} v_{2m+1} = a_1\alpha\alpha_1^m + b_1\beta\beta_1^m.$$

Observe that the sequences $\{U_m\}$, $\{U'_m\}$, $\{V_m\}$ and $\{V'_m\}$ are non-degenerate binary recursive sequences. By proving the theorem separately for sequences $\{U_m\}$ and $\{V_m\}$, $\{U_m\}$ and $\{V'_m\}$, $\{U'_m\}$ and $\{V_m\}$, $\{U'_m\}$ and $\{V'_m\}$, there is no loss of generality in assuming that $([\alpha], [\beta]) = [1]$.

Denote by c_1, c_2, \dots effectively computable positive numbers depending only on A, K , the sequences $\{u_m\}$ and

$\{v_m\}$. We may assume that $m > c_1$ with c_1 sufficiently large. Then, since $\{u_m\}$ is non-degenerate, we see that $u_m \neq 0$. Let $0 < n < m$ satisfy $v_n \neq 0$ and suppose that (3) is valid. We suppose

$$(5) \quad \text{lcm } P(\Delta_{m,n}) < (\log m)^A.$$

Let π_1, \dots, π_s be all the rational primes satisfying $\pi_i | \Delta_{m,n}$ and $\pi_i > m^K$ for $1 < i < s$. Let $0 < \epsilon < 1$. We suppose that

$$(6) \quad s < + \epsilon (\log m) (\log \log m)^{-1}.$$

We shall arrive at a contradiction for a suitable choice of ϵ depending only on A, K the sequences $\{u_m\}$ and $\{v_m\}$.

We write

$$(7) \quad B_1 = \frac{u_m}{(u_m, v_n)}, \quad B_2 = \frac{v_n}{(u_m, v_n)}, \\ \Delta = (u_m, v_n).$$

When

$$(8) \quad \frac{u_m}{v_n} = \frac{B_1}{B_2} \quad \text{and} \quad (B_1, B_2) = 1.$$

Further

$$(9) \quad \Delta_{m,n} = \pm B_1 B_2.$$

For a prime p dividing B_1 , we see from (7) that

$$\text{ord}_p(B_1) < \text{ord}_p(u_m).$$

Let \wp be a prime ideal in the ring of integers of $\mathcal{Q}(\alpha)$ dividing p . Then, since the ideals $[\alpha]$ and $[\beta]$ are relatively prime, either \wp does not divide $[\alpha]$ or \wp does not divide $[\beta]$. For simplicity assume that \wp does not divide $[\alpha]$. Then, by (1), we have

$$\begin{aligned} \text{ord}_p(u_m) &< \text{ord}_{\wp}(u_m) \\ &< c_2 + \text{ord}_{\wp} \left(-\frac{b}{a} \left(\frac{\beta}{\alpha} \right)^m - 1 \right). \end{aligned}$$

Now we apply theorem B with $n = 2$, $D = d$, $\alpha_1 = -b/a$, $\alpha_2 = \beta/\alpha$, $b_1 = 1$ and $b_2 = m$ to conclude that

$$\begin{aligned} \text{ord}_{\wp} \left(-\frac{b}{a} \left(\frac{\beta}{\alpha} \right)^m - 1 \right) \\ < c_3 p^d (\log p)^{-1} (\log m)^2. \end{aligned}$$

Therefore

$$\text{ord}_p(B_1) < c_4 p^d (\log p)^{-1} (\log m)^2.$$

This inequality follows similarly when \wp does not divide $[\beta]$. Consequently, by (4),

$$\sum_{\substack{p|B_1 \\ p < m^K}} \text{ord}_p(B_1) \log p < c_4 m^\tau (\log m)^2.$$

Similarly

$$\sum_{\substack{p|B_2 \\ p < m^K}} \text{ord}_p(B_2) \log p < c_5 m^\tau (\log m)^2.$$

Consequently, by (9), we may write

$$(10) \quad B_1 = B_3 \pi_1^{x_1} \dots \pi_s^{x_s}, \quad B_2 = B_4 \pi_1^{y_1} \dots \pi_s^{y_s}$$

where $x_1, \dots, x_s, y_1, \dots, y_s$ are non-negative integers and

$B_3, B_4 \in \mathbb{Z}$ with

$$(11) \quad \log \max(|B_3|, |B_4|) < c_6 m^\tau (\log m)^2.$$

Further we see from (7) that

$$\log \max (|B_1|, |B_2|) < c_7 m$$

which, together with (10), implies that

$$(12) \quad \max (x_1, \dots, x_s, y_1, \dots, y_s) < c_8 m$$

with $c_8 > 1$.

We have

$$(13) \quad u_m a_1^{-1} a \alpha^{m-n} v_n \\ = -b_1 \beta^n (a_1^{-1} a \alpha^{m-n} - b_1^{-1} b \beta^{m-n})$$

and, by (7) and (1),

$$(14) \quad \Lambda B_1^{-1} a \alpha^m = b \beta^m$$

In view of (3), we see that

$$(15) \quad u_m a_1^{-1} a \alpha^{m-n} v_n \neq 0.$$

Put

$$T = a_1^{-1} a \alpha^{m-n} v_n u_m^{-1} - 1,$$

$$T_1 = a^{-1} \alpha^{-m} \Lambda B_1^{-1} - 1.$$

By (15) and (14), notice that

$$TT_1 \neq 0.$$

Further it follows from (8) and (10) that

$$T_1 = a_1^{-1} \alpha^{-m} \pi_1^{x_1} \dots \pi_s^{x_s} (B_3 \Lambda) - 1$$

$$\text{and } T = \frac{a}{a_1} \alpha^{m-n} \pi_1^{z_1} \dots \pi_s^{z_s} \frac{B_4}{B_3} - 1$$

where $z_i = y_i - x_i$ for $1 < i < s$. Now we split the proof of theorem 3 in two cases.

Case I. $|\alpha| > |\beta|$. Dividing both the sides of (13) by u_m , we have

$$(16) \quad 0 < |T| < c_9^{-n}, \quad c_9 > 1.$$

We apply theorem μ with

$$n = s + 3 < \varepsilon (\log m) (\log \log m)^{-1} + 3 \text{ by (6),}$$

$$D = d < 2, \quad \log A_1 = \log A_2 = c_{10}, \quad \log A_3 = \dots =$$

$$\log A_{n-1} = (\log m)^A \text{ by (5), } \log A_n = c_6 m^\tau (\log m)^2 \text{ by (11)}$$

and $B = c_8 m$ by (12) to conclude that

$$(17) \quad |T| > \exp(-m^{\tau+c_{11}} \varepsilon (\log m)^5).$$

We shall choose ε to satisfy

$$(18) \quad \varepsilon < (1-\tau)/2 c_{11}.$$

Put

$$\tau_1 = (1 + \tau)/2.$$

Then, since $0 < \tau < 1$, we find that $\tau < \tau_1 < 1$.

Combining (16), (17) and (18), we have

$$n < c_{12} m^{\tau_1} (\log m)^5.$$

Then

$$(19) \quad \log |\wedge| < \log |v_n| < c_{13} m^{\tau_1} (\log m)^5.$$

Dividing both the sides of (14) by a d^m , we have

$$(20) \quad 0 < |T_1| < c_{14}^{-m}, \quad c_{14} > 1.$$

We apply theorem A with $n = s + 3 < \varepsilon (\log m) (\log \log m)^{-1} + 3$ by (6), $D = d < 2$, $\log A_1 = \log A_2 = c_{15}$,

$$\log A_3 = \dots = \log A_{n-1} = (\log m)^A \text{ by (5), } \log A_n = 2c_{13} m^{\tau_1}$$

$(\log m)^5$ by (19), (11) and $B = c_8 m$ by (12) to conclude that

$$(21) \quad |T_1| > \exp(-m^{\tau_1 + c_{16}\epsilon} (\log m)^8).$$

Let

$$\epsilon = \min \left(\frac{1 - \tau_1}{2c_{11}}, \frac{1 - \tau_1}{2c_{16}}, \frac{1}{2} \right)$$

Then (18) is satisfied. Put

$$\tau_2 = (1 + \tau_1) / 2.$$

Observe that $\tau_1 < \tau_2 < 1$. Now we combine (20) and (21) to conclude that

$$m \leq c_{17} m^{\tau_2} (\log m)^8$$

which, since $\tau_2 < 1$, implies that $m < c_{18}$. But this is not possible if $c_1 > c_{18}$.

Case II

$|\alpha| = |\beta|$. Let τ_1 and τ_2 be defined as in case I.

Observe that β is not a unit, since α/β is not a root of unity. Therefore there exists a prime ideal \mathfrak{p} in the ring of integers of $\mathbb{Q}(\alpha)$ such that $\mathfrak{p} \mid [\beta]$. Further, since the ideals $[\alpha]$ and $[\beta]$ are relatively coprime, observe that \mathfrak{p} does not divide $[\alpha]$. Consequently $\text{ord}_{\mathfrak{p}}(u_m) \leq c_{19}$. Now, by counting the power

of prime ideal \mathfrak{p} on both the sides in (13), we have

$$n \leq c_{20} + \text{ord}_{\mathfrak{p}}(u_m) + \text{ord}_{\mathfrak{p}}(T) \leq c_{21} + \text{ord}_{\mathfrak{p}}(T).$$

We apply theorem B with $p < c_{22}$ and the same parameters as in case I for obtaining a lower bound for $|\Gamma|$ by theorem A. We obtain

$$\text{ord}_{\wp}(\Gamma) < m^{\tau + c_{23}\epsilon} (\log m)^5.$$

We shall choose ϵ to satisfy

$$(22) \quad \epsilon < \frac{1 - \tau}{2c_{23}}.$$

Then

$$n < c_{24} m^{\tau_1} (\log m)^5$$

which implies that

$$\log | \wedge | < c_{25} m^{\tau_1} (\log m)^5.$$

Counting the power of prime ideal \wp on both the sides in (14), we obtain

$$m < c_{26} + \text{ord}_{\wp}(\Gamma_1).$$

We apply theorem B with $p < c_{22}$, $\log A_n = c_{25} m^{\tau_1} (\log m)^5$ and the same parameters as in case I for obtaining a lower bound for $|\Gamma_1|$ by theorem A. We obtain

$$\text{ord}_{\wp}(\Gamma_1) < m^{\tau_1 + c_{27}\epsilon} (\log m)^8.$$

Let

$$\epsilon = \min \left(\frac{1 - \tau}{2c_{23}}, \frac{1 - \tau_1}{2c_{27}}, \frac{1}{2} \right)$$

Then (22) is satisfied. We obtain

$$m < c_{28} m^{\tau_2} (\log m)^8.$$

Consequently $m < c_{29}$ which is not possible if $c_1 > c_{29}$.

This completes the proof of theorem 3.

Remarks

(i) Let $\{u_m\}$ be a non-degenerate binary recursive sequence. For every pair m, n with $m > n$, $u_m u_n \neq 0$ and $Q(u_m) = Q(u_n)$, we have

$$m - n > c_{30} (\log m)^2 (\log \log m)^{-1}$$

where $c_{30} > 0$ is an effectively computable number depending only on the sequence $\{u_m\}$. This follows immediately from theorem 1 and the relation (13) with $a_1 = a$, $b_1 = b$.

(ii) Let $P \geq 2$ and denote by S the set of all non-zero integers composed of primes not exceeding P . We can apply the argument of proof of theorem 1 to prove that for every $x \in S, y \in S$ with $(x, y) = 1, |x| > |y|$ and $\log |x| > e^e$,

$$\log Q(x+y) \geq c_{31} (\log \log |x|)^2 (\log \log \log |x|)^{-1}$$

where $c_{31} > 0$ is an effectively computable number depending only on P .

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