

A Continued Fraction Algorithm for Real Algebraic Numbers*

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Abstract. Let α denote a real algebraic number that is a root of a polynomial $f(x) \in \mathbf{Z}[x]$. The purpose of this paper is to state an algorithm for finding the simple continued fraction expansion of α . Furthermore, an application of the algorithm to sign determination in real algebraic number fields is given.

1. Introduction. The task of constructively computing the simple continued fraction expansion (see [2]) for a real root α of a polynomial

$$f(x) = b_0x^m + b_1x^{m-1} + \cdots + b_m \quad (b_0 \neq 0)$$

over the rational integers \mathbf{Z} raises no essential difficulties provided that α is the sole real root of $f(x)$. However, if $f(x)$ happens to have more than one real root, the problem arises of discriminating between the continued fraction expansion of α and of the other real roots of $f(x)$.

An attempt to solve this problem was made by Zassenhaus [5], who showed that, after a finite number of steps, the so-called "reduced state" of the continued fraction expansion of α (see below) is reached. (See also [2].) From there on, the discrimination of the real roots is automatically guaranteed. Unfortunately, no indication is given in Zassenhaus' method as to when the reduced state will be attained for a given α , nor does there seem to exist a simple device for achieving that state (cf. [6]). Nonetheless, a computer program was written by Smith [3] in which the method is applied to some special cases.

2. The Continued Fraction Algorithm. In this paper, we describe a different continued fraction algorithm that furnishes a solution to the discrimination problem mentioned above and that, moreover, appears to be much simpler than the routine designed by Zassenhaus [5].

Let us first remark that, as Zassenhaus [5] observed, it is expedient to reduce $f(x)$ to a polynomial having no multiple factors. We can eliminate them by replacing $f(x)$ by the polynomial $f(x)/(f(x), f'(x))$. In the trivial case in which α is a *rational* root of $f(x)$, the algorithm will simply terminate after a finite number of steps.

We confine ourselves therefore to giving a description of the algorithm as applied to an *irrational* real root α of the (not necessarily irreducible) polynomial $f(x)$ in $\mathbf{Z}[x]$.

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The polynomial $f(x)$ may, moreover, be supposed to have no rational roots at all. The continued fraction expansion of α is then calculated assuming that α is isolated by rational numbers (or infinity) r and s ; i.e., α is the unique root of $f(x)$ in the closed interval $[r, s]$. Put $r_0 = r, s_0 = s$, and define the 0 th successor α_0 of α by

$$\alpha_0 = \alpha,$$

the 0 th partial denominator a_0 of α by

$$a_0 = [\alpha_0],$$

where $[\]$ designates the greatest integer function, and the 0 th successor polynomial $f_0(x)$ of $f(x)$ by

$$f_0(x) = f(x).$$

We have $f_0(\alpha_0) = 0$.

Let us assume by induction that, for an integer $n \geq 1, \alpha_{n-1}$ is an irrational real root of a polynomial

$$f_{n-1}(x) = b_{0,n-1}x^m + b_{1,n-1}x^{m-1} + \dots + b_{m,n-1} \\ (b_{0,n-1} \neq 0), (b_{i,0} = b_i \text{ for } 0 \leq i \leq m),$$

over \mathbf{Z} having neither multiple factors nor rational roots, and that α_{n-1} is the unique root of $f_{n-1}(x)$ in the closed interval $[r_{n-1}, s_{n-1}]$.

Next, put $a_{n-1} = [\alpha_{n-1}]$, and let

$$r_n = (s_{n-1} - a_{n-1})^{-1} \text{ if } s_{n-1} < a_{n-1} + 1, \\ = 1 \text{ otherwise,} \\ s_n = (r_{n-1} - a_{n-1})^{-1} \text{ if } r_{n-1} > a_{n-1}, \\ = \infty \text{ otherwise.}$$

Define the n th successor α_n of α by

$$\alpha_n = (\alpha_{n-1} - a_{n-1})^{-1},$$

the n th partial denominator a_n of α by

$$a_n = [\alpha_n],$$

and the n th successor polynomial $f_n(x)$ of $f(x)$ by

$$f_n(x) = x^m f_{n-1}(x^{-1} + a_{n-1}).$$

Clearly, $f_n(x)$ is a polynomial over \mathbf{Z} having neither multiple factors nor rational roots, and α_n is one of the irrational real roots of $f_n(x)$. Moreover, α_n is the unique root of $f_n(x)$ in the closed interval $[r_n, s_n]$. Note that for $n \geq 1$, we have $\alpha_n > 1$ and $1 \leq r_n < s_n \leq \infty$.

The definition of r_n, s_n and α_n leads us to the following observation which is of significance for the discrimination problem mentioned at the beginning (cf. [2] and the Theorem of Vincent [4]).

THEOREM. *Under the above hypothesis on α , r , and s , there exists n_1 such that, for all $n \geq n_1$, we have*

$$r_n = 1 \quad \text{and} \quad s_n = \infty .$$

Proof. The assertion results from two facts that are immediate consequences of the definition of r_n , s_n and α_n .

(1) If $r_n = 1$ or $s_n = \infty$ for some integer $n \geq 1$, then it follows that

$$r_{n+i} = 1 \text{ for all even } \textit{or} \text{ all odd natural numbers } i, \\ \text{respectively,}$$

and that

$$s_{n+j} = \infty \text{ for all odd } \textit{or} \text{ all even natural numbers } j, \\ \text{respectively.}$$

(2) For all integers $n \geq 1$, the following hold:

$$\textit{either } r_n = 1 \textit{ or } a_{n-1} = [s_{n-1}]$$

and

$$\textit{either } s_n = \infty \textit{ or } a_{n-1} = [r_{n-1}].$$

Once we have arrived at an index $n_1 \geq 1$ such that $r_{n_1} = 1$ and $s_{n_1} = \infty$, statement (1) implies that $r_n = 1$ and $s_n = \infty$ for all $n \geq n_1$. To see that n_1 exists, consider the sequences $S = \{[r_0], [s_1], [r_2], \dots\}$ and $T = \{[s_0], [r_1], [s_2], \dots\}$, which are initially the continued fraction expansions of r and s , respectively. By (2), S and T must each eventually differ from the continued fraction expansion $\{a_0, a_1, a_2, \dots\}$ of α since $r \neq \alpha$ and $s \neq \alpha$. S and T each then become $\{\dots, 1, \infty, 1, \infty, \dots\}$.

The actual determination of the partial denominators a_n of α can now be carried through in the following manner (see also [5]).

First, we find improved bounds for the irrational real root α_n of $f_n(x)$ where $n \geq 0$. To this end, we have to introduce the set

$$\alpha_n = \alpha_n^{(1)}, \alpha_n^{(2)}, \dots, \alpha_n^{(m)}$$

of the complex roots of $f_n(x)$. We recall that these roots can be defined inductively by setting $\alpha_0^{(i)} = \alpha^{(i)}$ and, for $n \geq 1$,

$$\alpha_n^{(i)} = (\alpha_{n-1}^{(i)} - a_{n-1})^{-1} \quad (i = 1, 2, \dots, m).$$

Also, we use the n th convergent of the continued fraction expansion of α , that is, the fraction (see [2])

$$[a_0, a_1, \dots, a_n] = p_n/q_n \quad (p_n, q_n \in \mathbf{Z}).$$

As usual, define $p_{-1} = 1$ and $q_{-1} = 0$.

The integers p_{n-1} , p_{n-2} and q_{n-1} , q_{n-2} ($n \geq 1$) appear in the formula connecting $\alpha^{(i)}$ with $\alpha_n^{(i)}$, namely,

$$\alpha^{(i)} = (p_{n-1}\alpha_n^{(i)} + p_{n-2})/(q_{n-1}\alpha_n^{(i)} + q_{n-2}) \quad (i = 1, 2, \dots, m)$$

or, conversely,

$$\alpha_n^{(i)} = -(q_{n-2}\alpha^{(i)} - p_{n-2})/(q_{n-1}\alpha^{(i)} - p_{n-1}).$$

We write the latter relation for $n \geq 2$ in the form

$$\alpha_n^{(i)} = -\frac{\alpha^{(i)} - p_{n-2}/q_{n-2} \cdot q_{n-2}}{\alpha^{(i)} - p_{n-1}/q_{n-1} \cdot q_{n-1}} \quad (i = 1, 2, \dots, m).$$

Noting that $p_{n-2}/q_{n-2} \rightarrow \alpha$ and $p_{n-1}/q_{n-1} \rightarrow \alpha$, as $n \rightarrow \infty$, and that $\alpha \neq \alpha^{(i)}$ for all i in the interval $1 < i \leq m$, we conclude that, for $i \neq 1$ and for all large n , the $|\alpha_n^{(i)}|$ are asymptotic to q_{n-2}/q_{n-1} . On the other hand, it follows from the second of the two relations

$$\begin{aligned} p_{n-1} &= p_{n-2}a_{n-1} + p_{n-3} \\ q_{n-1} &= q_{n-2}a_{n-1} + q_{n-3} \end{aligned} \quad (n \geq 2),$$

or, respectively, from the definition of q_{-1} and q_0 that

$$q_{n-2}/q_{n-1} \leq a_{n-1}^{-1} \quad (n \geq 2)$$

with strict inequality for $n \geq 3$. For all large n , the conjugates $\alpha_n^{(i)}$ of $\alpha_n = \alpha_n^{(1)}$ satisfy

$$|\alpha_n^{(i)}| < a_{n-1}^{-1} \quad (1 < i \leq m).$$

It is clear from the above relations that there exists n_2 such that, for all $n \geq n_2$, the following two conditions are fulfilled:

$$\begin{aligned} \alpha_n &> 1, \\ 0 &< -\operatorname{Re}(\alpha_n^{(i)}) \leq |\alpha_n^{(i)}| < 1 \quad (1 < i \leq m), \end{aligned}$$

where “Re” denotes the real part of a complex number. This is what Zassenhaus [5] calls the *reduced state* of the continued fraction expansion of α . Thus, for all large n , α_n is a *PV* number.

As soon as the reduced state is reached, we know, because of the relation

$$\sum_{i=1}^m \alpha_n^{(i)} = -b_{1,n}/b_{0,n}$$

on the roots $\alpha_n^{(i)}$ of $f_n(x)$, that $\alpha_n = \alpha_n^{(1)}$ lies in the interval

$$-b_{1,n}/b_{0,n} < \alpha_n < (m - 1) - b_{1,n}/b_{0,n}.$$

The upper bound for α_n can be further improved. Specifically, from the relations derived above, we infer that α_n is asymptotic to $(m - 1)q_{n-2}/q_{n-1} - b_{1,n}/b_{0,n}$ and moreover, that there exists n_3 such that, for all $n \geq n_3$, we have

$$\alpha_n < (m - 1)/a_{n-1} - b_{1,n}/b_{0,n}.$$

Now, if $n \geq 1$ and a_0, a_1, \dots, a_{n-1} are already computed, we calculate a_n via a modified binary search process in the interval $u_n \leq a_n \leq v_n$ which is roughly defined as follows. Put

$$n_4 = \max\{n_1, n_2, n_3\},$$

where n_i are the preceding index bounds. Then, we put for $n < n_4$,

$$\begin{aligned} u_n &= [r_n] \quad \text{if } n \text{ is even,} \\ &= [s_n], \quad \text{if } n \text{ is odd,} \end{aligned}$$

$$v_n = \min\{[s_n], [t_n]\}, \text{ if } n \text{ is even,}$$

$$= \min\{[r_n], [t_n]\}, \text{ if } n \text{ is odd,}$$

where

$$t_n = 1 + \max_{1 \leq i \leq m} \{|b_{i,n}|/|b_{0,n}|\},$$

and, for $n \geq n_4$,

$$u_n = \max\{1, [-b_{1,n}/b_{0,n}]\},$$

$$v_n = [(m - 1)/a_{n-1} - b_{1,n}/b_{0,n}].$$

Note that, for $n \geq 1$, u_n and v_n are positive integers.

The n th partial denominator a_n of α is then determined as the unique natural number λ_n in the interval $u_n \leq \lambda_n \leq v_n$ for which

$$\text{sgn } f_n(\lambda_n) \neq \text{sgn } f_n(\lambda_n + 1).$$

Before describing the binary search process for a_n , we note that, if $n \geq n_4$, it is expedient to precede the binary search with the sign test for

$$\lambda_n = [(m - 1)q_{n-2}/q_{n-1} - b_{1,n}/b_{0,n}],$$

because the number in square brackets is, as we have seen, a good approximation to α_n . This, of course, requires computation of the q_n . If $\text{sgn } f_n(\lambda_n) \neq \text{sgn } f_n(\lambda_n + 1)$ for this λ_n , then $a_n = \lambda_n$. Otherwise, we start the binary search as follows. We put $\lambda_n = v_n$ and check whether $\text{sgn } f_n(\lambda_n) \neq \text{sgn } f_n(\lambda_n + 1)$. If so, then $a_n = v_n$. If not, we know that $u_n \leq a_n \leq v_n - 1$. Unless $u_n = v_n - 1$, in which case $a_n = u_n$, we put

$$w_n = [\frac{1}{2}(u_n + v_n)]$$

and compare the signs of $f_n(w_n)$ and $f_n(v_n)$, say. If they differ, we replace u_n by w_n ; otherwise, we leave u_n unchanged and substitute w_n for v_n . The search process is then repeated (if need be) with respect to the new interval, until $u_n = v_n - 1$.

This algorithm has been implemented as a computer program which we shall use to build the example of Section 4.

3. An Application of the Algorithm to Sign Determination. In this section, we shall outline a method for performing sign determination in a real algebraic number field

$$K = \mathbb{Q}(\alpha)$$

over the field of rational numbers \mathbb{Q} , where α is an irrational real root of a (not necessarily irreducible) polynomial $f(x)$ in $\mathbb{Z}[x]$ of degree $m > 1$ as before. This method seems to be somewhat simpler than the one proposed by Kempfert [1] and Zassenhaus [6]; however, their method applies to any ordered field.

Every element $\beta \in K$ can be represented in the form $\beta = g(\alpha)$ with a polynomial $g(x)$ in $\mathbb{Q}[x]$ of degree $< m$.

First of all, we may assume that $g(\alpha) \neq 0$, since if $g(\alpha)$ were 0, then $(f(x), g(x)) \neq 1$.

To determine the sign of $g(\alpha)$, we employ the continued fraction algorithm of Section 2 in order to approximate α by its convergents p_n/q_n . The theory of continued

fractions yields, for the approximation of α by p_n/q_n , the estimate (see [2])

$$|\alpha - p_n/q_n| < 1/q_n^2,$$

where $q_n \rightarrow \infty$, as $n \rightarrow \infty$.

We shall show that, for all large n , the sign of $g(\alpha)$ can be obtained from the relation

$$\operatorname{sgn} g(\alpha) = \operatorname{sgn} g(p_n/q_n).$$

To this end, we note that, by the mean value theorem (cf. [6]), the formula

$$g(\alpha) - g(p_n/q_n) = g'(\xi)(\alpha - p_n/q_n)$$

is valid, where $g'(x)$ denotes the derivative of $g(x)$ and ξ is a real number lying between α and p_n/q_n . Let M be a bound for $g'(x)$ for x , say between p_0/q_0 and p_1/q_1 . We thus have

$$|g(\alpha) - g(p_n/q_n)| < M/q_n^2.$$

Then $g(p_n/q_n) \rightarrow g(\alpha)$. For large enough n , $|g(p_n/q_n)| \geq M/q_n^2$ and then $\operatorname{sgn} g(p_n/q_n) = \operatorname{sgn} g(\alpha)$.

4. An Example for the Continued Fraction Algorithm. We compute here the continued fraction expansion for three roots of the polynomial

$$f(x) = x^7 - 7x + 3,$$

which has three irrational real roots and four complex roots.

In the table which follows, the first column contains n , the second, third, and fourth contain the a_n for the three real roots $\alpha^{(1)} \sim -1.444 \dots$, $\alpha^{(2)} \sim 0.429 \dots$, $\alpha^{(3)} \sim 1.233$.

n	$\alpha^{(1)}$	$\alpha^{(2)}$	$\alpha^{(3)}$
0	-2	0	1
1	1	2	3
2	1	3	2
3	3	53	2
4	1	5	4
5	86	1	15
6	63	2	4
7	1006	1	1
8	2	1	7
9	1	1	70
10	3	1	1
11	3	91	7
12	2	1	2
13	3	1	1
14	1	1	8
15	1	5	4

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