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► **To cite this version:**

Elias Tsigaridas. Improved bounds for the CF algorithm. Theoretical Computer Science, 2012, pp.1-12. hal-00776230

HAL Id: hal-00776230

<https://inria.hal.science/hal-00776230>

Submitted on 15 Jan 2013

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Improved bounds for the CF algorithm

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January 15, 2013

Abstract

We consider the problem of isolating the real roots of a square-free polynomial with integer coefficients using the classic variant of the continued fraction algorithm (CF), introduced by Akritas. We compute a lower bound on the positive real roots of univariate polynomials using exponential search. This allows us to derive a worst case bound of $\tilde{O}_B(d^4\tau^2)$ for isolating the real roots of a polynomial with integer coefficients using the *classic variant of CF*, where d is the degree of the polynomial and τ the maximum bitsize of its coefficients. This improves the previous bound of Sharma by a factor of d^3 and matches the bound derived by Mehlhorn and Ray for another variant of CF which is combined with subdivision; it also matches the worst case bound of the classical subdivision-based solvers STURM, DESCARTES, and BERNSTEIN.

1 Introduction

The problem of isolating the real roots of a square-free polynomial with integer coefficients is one of the most well-studied problems in symbolic computation and computational mathematics. The goal is to compute intervals with rational endpoints that contain one and only one real root of the polynomial, and to have one interval for every real root.

Numerical algorithms approximate the roots, real and complex, of the input polynomials up to a precision. They could be turned to root isolation algorithms by requiring them to approximate up to the separation bound, that is the minimum distance between the roots. The crux of the algorithms is that they recursively split the polynomial until we obtain linear factors that approximate sufficiently all the roots, real and complex. The algorithm of Schönhage [31], see also [32] achieves a bound of $\tilde{O}_B(d^3\tau)$, by recursively slitting out linear factors. The best known bound for the problem is due to Pan [26]. He achieves a bound $\tilde{O}_B(d^2\tau)$, which is optimal up to polylogarithmic factors; we also refer the reader to [13, Section 3.1]. The algorithm exploits a divide and conquer approach for splitting, recursively, the polynomial into factors of degrees $d/12$ and $d - d/12$, which results to $\log(d)$ splitting levels and saves a factor of $d/\log(d)$, with respect to the previous known approaches [23]. We refer the reader to [24, 25] for review of the various approaches. For a recent approach that concentrates only on the real roots we refer to [27]. For an implementation of Schönhage's algorithm we refer the reader to the routine CPRTS, p.12 in Addenda, based on the

multitape Turing machine¹. We are not aware of any implementation of Pan’s algorithm. Quite recently, Sagraloff [29] announced a variant of the bitstream version of DESCARTES algorithm with complexity $\tilde{O}_B(d^3\tau^2)$, and an algorithms that combines DESCARTES with Newton iterations for isolating the real roots, with complexity $\tilde{O}_B(d^3\tau)$ [30].

If we restrict ourselves to algorithms that perform computations with rational numbers of arbitrary precision, then we can distinguish two main categories. The first one consists of algorithms that are subdivision-based; their process mimics binary search. They bisect an initial interval that contains all the real roots until they obtain intervals with one or zero real roots. The different variants differ in the way that they count the number of real roots inside an interval, for example using Sturm’s theorem or Descartes’ rule of signs, see also Th. 1. Classical representatives are the algorithms STURM, DESCARTES and BERNSTEIN. We refer the reader to [10, 12, 8, 18, 17, 15, 9, 28] and references therein for further details. The worst case complexity of all variants in this category is $\tilde{O}_B(d^4\tau^2)$, where d is the degree of the polynomial and τ the maximum bitsize of its coefficients. Especially, for the STURM solver, recently, it was proved that its expected complexity, if we consider certain random polynomials as input, is $\tilde{O}_B(r d^2\tau)$, where r is the number of real roots [11]. Let us also mention the bitstream version of DESCARTES algorithm, cf. [21] and references therein.

The second category contains algorithms that isolate the real roots of a polynomial by computing their continued fraction expansion (CF). Since successive approximants of a real number define an interval that contains this number, CF computes the partial quotients of the roots of the polynomial until the corresponding approximants correspond to intervals that isolate the real roots. Counting of the real roots is based on Descartes’ rule of signs (Th. 1) and termination is guaranteed by Vincent’s theorem (Th. 3). There are several variants which differ in the way how they compute the partial quotients.

The first formulation of the algorithm is due to Vincent [39], who computed the partial quotients by successive transformations of the form $x \mapsto x + 1$. An upper bound on the number of partial quotients needed was derived by Uspensky [37]. Unfortunately this approach leads to an exponential complexity bound. Akritas [1], see also [4, 2], treated the exponential behavior of CF by treating the partial quotients as lower bounds of the positive real roots, and computed the bounds using Cauchy’s bound. With this approach, c repeated operations of the form $x \mapsto x + 1$ could be replaced by $x \mapsto x + c$. However, his analysis assumes an ideal positive lower bound, that is that we can compute directly the floor of the smallest positive real root. In [35], it was proven, under the assumption that Gauss-Kuzmin distribution holds for the real algebraic numbers, that the expected complexity of CF is $\tilde{O}_B(d^4\tau^2)$. By spreading the roots, the expected complexity becomes $\tilde{O}_B(d^4 + d^3\tau)$ [36]. The first worst-case complexity result of CF, $\tilde{O}_B(d^8\tau^3)$, is due to Sharma [33], without any assumption. He also proposed a variant of CF, that combines continued fractions with subdivision, with complexity $\tilde{O}_B(d^5\tau^2)$. All the variants of CF in [33] compute lower bounds on the positive roots using Hong’s bound [14], which was believed to have quadratic arithmetic complexity. Mehlhorn and Ray [20] proposed a novel way of computing Hong’s bound based on incremental convex hull computations with (soft) linear arithmetic complexity. A direct consequence is that they reduced the complexity of the variant of CF combined with subdivision [33] to $\tilde{O}_B(d^4\tau^2)$, thus matching the worst case complexity of the subdivision-based algorithms. Using [20] and fast Taylor shifts [40], the bound [33] on *classical variant of CF* becomes $\tilde{O}_B(d^7\tau^3)$.

In this paper we present and analyse a way to compute a lower bound on the positive real roots

¹<http://www.iai.uni-bonn.de/~schoe/tp/TPpage.html>

of a univariate polynomial (Lem. 5) using exponential search. The proposed approach computes the floor of the root (possible complex) with the smallest positive real part that contributes to the number of the sign variations in the coefficients list of the polynomial. Our bound is at least as good as Hong's bound [14]. Using this lower bound we improve the worst case bit complexity bound of the *classical variant of CF*, obtained by Sharma [33], by a factor of d^3 . We obtain a bound of $\tilde{\mathcal{O}}_B(d^4\tau^2)$ or $\tilde{\mathcal{O}}_B(N^6)$, where $N = \max\{d, \tau\}$, (Th. 7), which matches the worst case bound due to Mehlhorn and Ray [20] achieved for variant of CF that is combined with subdivision.. It also matches the worst case bound of the classical subdivision-based solvers STURM [12, 8, 9], DESCARTES [10, 12, 18, 17, 15, 28], and BERNSTEIN [10, 12].

A preliminary version of this work appeared in [34].

The rest of the paper is structured as follows. First we specify our notation. Sec. 2 presents a short introduction to the theory of continued fractions. In Sec. 3 we present the algorithm to compute lower bounds and we derive the worst case complexity bound of CF.

Notation. In what follows \mathcal{O}_B , resp. \mathcal{O} , means bit, resp. arithmetic, complexity and the $\tilde{\mathcal{O}}_B$, resp. $\tilde{\mathcal{O}}$, notation means that we are ignoring logarithmic factors. For a polynomial $A \in \mathbb{Z}[x]$, $\deg(A) = d$ denotes its degree and $\mathcal{L}(A) = \tau$ the maximum bitsize of its coefficients, including a bit for the sign. For $a \in \mathbb{Q}$, $\mathcal{L}(a) \geq 1$ is the maximum bitsize of the numerator and the denominator. Let $M(\tau)$ denote the bit complexity of multiplying two integers of size τ ; using FFT, $M(\tau) = \tilde{\mathcal{O}}_B(\tau)$. To simplify notation, we will assume throughout the paper that $\lg(\deg(A)) = \lg d = \mathcal{O}(\tau) = \mathcal{O}(\mathcal{L}(A))$. By $\text{VAR}(A)$ we denote the number of sign variations in the list of coefficients of A . We use Δ_γ to denote the minimum distance between a root γ of a polynomial A and any other root, we call this quantity *local separation bound*; $\Delta = \min_\gamma \Delta_\gamma$ is the *separation bound*, that is the minimum distance between all the roots of A .

2 A short introduction to continued fractions

Our presentation follows closely [36]. For additional details we refer the reader to, e.g., [41, 6, 38]. In general, a *simple (regular) continued fraction* is a (possibly infinite) expression of the form

$$q_0 + \frac{1}{q_1 + \frac{1}{q_2 + \dots}} = [q_0, q_1, q_2, \dots],$$

where the numbers q_i are called *partial quotients*, $q_i \in \mathbb{Z}$ and $q_i \geq 1$ for $i > 0$. Notice that q_0 may have any sign, however, in our real root isolation algorithm $q_0 \geq 0$, without loss of generality. By considering the recurrent relations

$$\begin{aligned} P_{-1} &= 1, & P_0 &= q_0, & P_{n+1} &= q_{n+1}P_n + P_{n-1}, \\ Q_{-1} &= 0, & Q_0 &= 1, & Q_{n+1} &= q_{n+1}Q_n + Q_{n-1}, \end{aligned} \tag{1}$$

it can be shown by induction that $R_n = \frac{P_n}{Q_n} = [q_0, q_1, \dots, q_n]$, for $n = 0, 1, 2, \dots$.

If $\gamma = [q_0, q_1, \dots]$ then $\gamma = q_0 + \frac{1}{Q_0Q_1} - \frac{1}{Q_1Q_2} + \dots = q_0 + \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{Q_{n-1}Q_n}$ and since this is a series of decreasing alternating terms it converges to some real number γ . A finite section $R_n = \frac{P_n}{Q_n} = [q_0, q_1, \dots, q_n]$ is called the n -th *convergent* (or *approximant*) of γ and the tails $\gamma_{n+1} =$

$[q_{n+1}, q_{n+2}, \dots]$ are known as its *complete quotients*. That is $\gamma = [q_0, q_1, \dots, q_n, \gamma_{n+1}]$ for $n = 0, 1, 2, \dots$. There is a one to one correspondence between the real numbers and the continued fractions, where evidently the finite continued fractions correspond to rational numbers.

It is known that $Q_n \geq F_{n+1}$ and that $F_{n+1} < \phi^n < F_{n+2}$, where F_n is the n -th Fibonacci number and $\phi = \frac{1+\sqrt{5}}{2}$ is the golden ratio. Continued fractions are the best rational approximation (for a given denominator size). This is as follows: $\frac{1}{Q_n(Q_{n+1}+Q_n)} \leq \left| \gamma - \frac{P_n}{Q_n} \right| \leq \frac{1}{Q_n Q_{n+1}} < \phi^{-2n+1}$.

In order to indicate or to emphasize that a partial quotient or an approximant belongs to a specific real number γ , we use the notation q_i^γ and $R_n^\gamma = P_n^\gamma / Q_n^\gamma$, respectively. We also use $q_i^{(k)}$ and $R_n^{(k)} = P_n^{(k)} / Q_n^{(k)}$, where k is a non-negative integer, to indicate that we refer to the (real part of the) root γ_k of a polynomial A . The ordering of the roots is considered with respect to the magnitude of their (positive) real part.

3 Worst case complexity of CF

Theorem 1 (Descartes' rule of sign). *The number R of real roots of $A(x)$ in $(0, \infty)$ is bounded by $\text{VAR}(A)$ and we have $R \equiv \text{VAR}(A) \pmod{2}$.*

Remark 2. *In general Descartes' rule of sign overestimates of the number of the positive real roots. However, if we know that A is hyperbolic, i.e. has only real roots, or when the number of sign variations is 0 or 1 then it counts exactly.*

The CF algorithm relies on the following theorem, which dates back to Vincent's theorem from 1836 [39]. The inverse of Th. 3 can be found in [3, 7, 22]. The version of the theorem that we present is due to Alesina and Galuzzi [5], see also [37, 1, 3, 2], and its proof is closely connected to the one and two circle theorems (refer to [18, 5] and references therein).

Theorem 3. [5] *Let $A \in \mathbb{Z}[x]$ be square-free and let $\Delta > 0$ be the separation bound, i.e. the smallest distance between two (complex) roots of A . Let n be the smallest index such that $F_{n-1} F_n \Delta > \frac{2}{\sqrt{3}}$, where F_n is the n -th Fibonacci number. Then the map $x \mapsto [c_0, c_1, \dots, c_n, x]$, where c_0, c_1, \dots, c_n is an arbitrary sequence of positive integers, transforms $A(x)$, after we clear the denominators, to $A_n(x)$, whose list of coefficients has no more than one sign variation.*

For a polynomial $A = \sum_{i=0}^d a_i x^i$, the Mahler measure, $\mathcal{M}(A)$, of A is $\mathcal{M}(A) = a_d \prod_{|\gamma| \geq 1} |\gamma|$, where γ runs through the (complex) roots of A , e.g. [22, 41]. If we further assume that $A \in \mathbb{Z}[x]$ and $\mathcal{L}(A) = \tau$ then $\mathcal{M}(A) \leq \|A\|_2 \leq \sqrt{d+1} \|A\|_\infty = 2^\tau \sqrt{d+1}$, and so $\prod_{|\gamma| \geq 1} |\gamma| \leq 2^\tau \sqrt{d+1}$.

We will also use the following aggregate bound. For various version of such bounds, we refer the reader to e.g. [36, 8, 9, 22, 15]. We use a version from [16].

Theorem 4. *Let $g \in \mathbb{R}[t]$ be an arbitrary polynomial of degree d and let $k := k(g) = \deg(\gcd(g, g'))$, where g' is the derivative of g . Let V be any subset of the roots of g , then*

$$\prod_{\gamma \in V} \Delta_\gamma = \mathcal{O}(d \lg(\mathcal{M}(g)) + \mathcal{L}(\mathbf{SR}_k(g, g')))$$

where \mathbf{SR}_k is the k -th polynomial in the subresultant sequence of g and g' . If $g \in \mathbb{Z}[x]$, $\mathcal{L}(g) = \tau$ and square-free, then aforementioned bound becomes $\prod_{\gamma \in V} \Delta_\gamma = \tilde{\mathcal{O}}(d\tau)$.

3.1 The tree

The CF algorithm relies on Vincent's theorem (Th. 3) and Descartes' rule of sign (Th. 1) to isolate the positive real roots of a square-free polynomial A . The negative roots are isolated after we perform the transformation $x \mapsto -x$; hence it suffices to consider only the case of positive real roots throughout the analysis.

The pseudo-code of the classic variant of CF is presented in Alg. 1.

Given a polynomial A , we compute the floor of the smallest positive real root (PLB = Positive Lower Bound), i.e. $b = \text{PLB}$. The *ideal* PLB is a function that can determine whether a polynomial has positive real roots, and if there are such roots then returns the floor of the smallest positive root of the polynomial.

Then we perform the transformation $x \mapsto x + b$, obtaining a polynomial A_b . It holds that $\text{VAR}(A) \geq \text{VAR}(A_b)$. The latter polynomial is transformed to A_1 by the transformation $x \mapsto 1 + x$ and if $\text{VAR}(A_1) = 0$ or $\text{VAR}(A_1) = 1$, then A_b has 0, resp. 1, real roots greater than 1, or equivalently A has 0, resp. 1, real roots greater than $b + 1$ (Th. 1). If $\text{VAR}(A_1) < \text{VAR}(A_b)$ then (possibly) there are real roots of A_b in $(0, 1)$, or equivalently, there are real roots of A in $(b, b + 1)$, due to Budan's theorem. We apply the transformation $x \mapsto 1/(1 + x)$ to A_b , and we get the polynomial A_2 . If $\text{VAR}(A_2) = 0$ or $\text{VAR}(A_2) = 1$, A_b has 0, resp. 1, real root less than 1 (Th. 1), or equivalently A has 0, resp. 1, real root less than $b + 1$, or to be more specific in $(b, b + 1)$ (Th. 1). If the transformed polynomials, A_1 and A_2 , have more than one sign variation, then we apply PLB to them and we repeat the process.

Following [1, 36, 33] we consider the process of the algorithm as an infinite binary tree. The nodes of the tree hold polynomials and (isolating) intervals. The root of the tree corresponds to the original polynomial A and the shifted polynomial A_b . The branch from a node to a right child corresponds to the map $x \mapsto x + 1$, which yields polynomial A_1 , while to the left child to the map $x \mapsto 1/(1 + x)$, which yields polynomial A_2 . The sequence of transformations that we perform is equivalent to the sequence of transformations in Th. 3, and so the leaves of the tree hold (transformed) polynomials that have no more than one sign variation, because of Th. 3.

A polynomial that corresponds to a leaf of the tree and has one sign variation it is produced after a transformation as in Th. 3, using positive integers q_0, q_1, \dots, q_n . The compact form of this is $M : x \mapsto \frac{P_n x + P_{n-1}}{Q_n x + Q_{n-1}}$, where $\frac{P_{n-1}}{Q_{n-1}}$ and $\frac{P_n}{Q_n}$ are consecutive convergents of the continued fraction $[q_0, q_1, \dots, q_n]$. The polynomial has one real root in $(0, \infty)$, thus the (unordered) endpoints of the isolating interval are $M(0) = \frac{P_{n-1}}{Q_{n-1}}$ and $M(\infty) = \frac{P_n}{Q_n}$.

There are different variants of the algorithm that differ in the way they compute PLB. A PLB realization that actually computes exactly the floor of the smallest positive real root is called *ideal*, but unfortunately has a prohibitive complexity.

A crucial observation is that Descartes' rule of sign (Th. 1), that counts the number of sign variations depends not only on positive real roots, but also on some complex ones; which have positive real part. Roughly speaking CF is trying to isolate the positive real parts of the roots of A that contribute to the sign variations. Thus, the ideal PLB only needs to compute the floor of the smallest positive real part of the roots of A that contribute to the number of sign variations. For this we will use Lem. 5. Notice that all the positive real roots contribute to the number of sign variation of A , but this is not always the case for the complex roots with positive real part.

3.2 Computing a partial quotient

Lemma 5. *Let $A \in \mathbb{Z}[x]$, such that $\deg(A) = d$ and $\mathcal{L}(A) = \tau$. We can compute the first partial quotient, or in the other words the floor², c , of the real part of the root with the smallest real part, that contributes to the sign variations of A in $\tilde{\mathcal{O}}_B(d\tau \lg c + d^2 \lg^2 c)$.*

Proof. We compute the corresponding integer using the technique of the exponential search, see for example [19]. Without loss of generality, we may assume that the real root is not in $(0, 1)$, since in this case we should return 0.

We perform the transformation $x \mapsto x + 2^0$ to the polynomial, and then the transformation $x \mapsto x + 1$. If the number of sign variations of the resulting polynomial compared to the original one decreases, then $2^0 = 1$ is the partial quotient. If not, then we perform the transformation $x \mapsto x + 2^1$. If the number of sign variations does not decrease, then we perform $x \mapsto x + 2^2$. Again if the number of sign variations does not decrease, then we perform $x \mapsto x + 2^3$ and so on. Eventually, for some positive integer k , there would be a loss in the sign variations between transformations $x \mapsto x + 2^{k-1}$ and $x \mapsto x + 2^k$. In this case the partial quotient c , which we want to compute, satisfies $2^{k-1} < c < 2^k < 2c$. The exact value of c is computed by performing binary search in the interval $[2^k, 2^{k+1}]$. We deduce that the number of transformations that we need to perform is $2k + \mathcal{O}(1) = 2\lg\lfloor c \rfloor + \mathcal{O}(1)$.

In the worst case, each transformation corresponds to an asymptotically fast Taylor shift with a number of bitsize $\mathcal{O}(\lg c)$, which costs³ $\mathcal{O}_B(M(d\tau + d^2 \lg c) \lg d)$ [40, Th. 2.4]. By considering fast multiplication algorithms the costs becomes $\tilde{\mathcal{O}}_B(d\tau + d^2 \lg c)$ and multiplying by the number of transformations needed, $\lg c$, we conclude the proof.

It is worth noticing that we need not consider the cases $c = 2^k$ or $c = 2^{k+1}$, since then we have computed, exactly, a rational root. \square

We could also compute the first partial quotient, c , with a procedure similar to the modification of the CF algorithm that is presented in [33]. If we assume that the lower bound computation used in [33] always returns a number smaller than one, then maps of the form $x \mapsto 2x$ and $x \mapsto x + 1$ are performed, that eventually compute the partial quotient. This might be more efficient in practice since these operations are simpler than a Taylor shift of the form $x \mapsto x + b$, where $b > 1$.

3.3 Shifts operations and total complexity

Up to some constant factors, we can replace Δ in Th. 3 by Δ_γ , see [33] for a proof. This allows us to estimate the number, m_γ , of partial quotients needed, in the worst case, to isolate the positive real part of a root γ . Using Eq. (12) from [33] we get

$$m_\gamma \leq \frac{1}{2}(1 + \log_\phi 2 - \log_\phi \Delta_\gamma) \leq 2 - \lg \Delta_\gamma.$$

The transformed polynomial has either one or zero sign variation and if $\gamma \in \mathbb{R}$, then the corresponding interval isolates γ from the other roots of A . The associated continued fraction of (the real part of) γ is $[q_0^\gamma, q_1^\gamma, \dots, q_{m_\gamma}^\gamma]$. It holds that $\sum_\gamma m_\gamma = \mathcal{O}(d^2 + d\tau)$ [36, 33]. The following lemma

²We choose to use c instead of q_0 because in the complexity analysis that follow A could be a result of a shift operation, thus the computed integer may not be the 0-th partial quotient of the root that we are trying to approximate.

³Following Th. 2.4(E) in [40] the cost of performing the operation $f(x+a)$, where $\deg(f) = n$, $\mathcal{L}(f) = \tau$ and $\mathcal{L}(a) = \sigma$ is $\mathcal{O}_B(M(n\tau + n^2\sigma) \lg n)$, and if we assume fast multiplication algorithms between integers, then it becomes $\tilde{\mathcal{O}}_B(n\tau + n^2\sigma)$.

bounds, obtained from the bounds in [33], bounds the bitsize of the partial quotients, q_k^γ , of a root γ .

Lemma 6. *Let $A \in \mathbb{Z}[x]$, such that $\deg(A) = d$ and $\mathcal{L}(A) = \tau$. For the real part of any root γ it holds*

$$\sum_{j=0}^{m_\gamma} \lg(q_j^\gamma) = \lg(q_0^\gamma) + \sum_{j=1}^{m_\gamma} \lg(q_j^\gamma) \leq \lg(q_0^\gamma) + 1 - \lg \Delta_\gamma,$$

where we assume that $q_0^\gamma > 0$, and the term $1 - \lg \Delta_\gamma$ appears only when $\Delta_\gamma < 1$, i.e. when $m_\gamma \geq 1$. Moreover $\sum_\gamma \lg(q_0^\gamma) \leq \lg \|A\|_2 \leq \tau + \lg d$ and if γ ranges over a subset of distinct roots of A , then

$$\sum_\gamma \sum_{k=0}^{m_\gamma} \lg q_k^\gamma \leq 1 + \tau + \lg d - \lg \prod_\gamma \Delta_\gamma = \tilde{\mathcal{O}}(d\tau).$$

Proof. The Mahler measure, $\mathcal{M}(A)$, of A is $\mathcal{M}(A) = a_d \prod_{|\gamma| \geq 1} |\gamma|$. It also holds $\mathcal{M}(A) \leq \|A\|_2 \leq \sqrt{d+1} \|A\|_\infty = 2^\tau \sqrt{d+1}$, and so $\prod_{|\gamma| \geq 1} |\gamma| \leq 2^\tau \sqrt{d+1}$. Since q_0^γ is the integer part of γ it holds $\prod_\gamma q_0^\gamma \leq \prod_{|\gamma| \geq 1} |\gamma| \leq \|A\|_2$ and thus

$$\sum_\gamma \lg(q_0^\gamma) \leq \lg \sqrt{d+1} + \lg \|A\|_\infty \leq \tau + \lg d. \quad (2)$$

Following [33] we know that

$$\frac{1}{Q_{m_\gamma}^\gamma Q_{m_\gamma-1}^\gamma} \geq \frac{\Delta_\gamma}{2} \Leftrightarrow Q_{m_\gamma}^\gamma Q_{m_\gamma-1}^\gamma \leq 2/\Delta_\gamma. \quad (3)$$

From Eq. (1) we get $Q_k = q_k Q_{k-1} + Q_{k-2} \Rightarrow Q_k \geq q_k Q_{k-1}$, for $k \geq 1$. If we apply the previous relation recursively we get $\prod_{k=1}^{m_\gamma} q_k^\gamma \leq Q_{m_\gamma}^\gamma \leq 2/\Delta_\gamma$ and $\prod_{k=1}^{m-1} q_k^\gamma \leq Q_{m_\gamma-1}^\gamma \leq 2/\Delta_\gamma$, and so

$$\sum_{k=1}^{m_\gamma} \lg q_k^\gamma = \lg \prod_{k=1}^{m_\gamma} q_k^\gamma \leq 1 - \lg \Delta_\gamma.$$

Finally, we sum over all roots γ and we use (2) and Th. 4,

$$\begin{aligned} \sum_\gamma \sum_{k=0}^{m_\gamma} \lg q_k^\gamma &= \sum_\gamma \lg q_0^\gamma + \sum_\gamma \sum_{k=1}^{m_\gamma} \lg q_k^\gamma \leq \sum_\gamma \lg q_0^\gamma + \sum_\gamma (1 - \lg \Delta_\gamma) \\ &\leq 1 + \tau + \lg d + \tilde{\mathcal{O}}(d\tau) = \tilde{\mathcal{O}}(d\tau), \end{aligned}$$

which completes the proof. \square

At each step of CF we compute a partial quotient and we apply a Taylor shift to the polynomial with this number. In the worst case we increase the bitsize of the polynomial by an additive factor of $\mathcal{O}(d \lg(q_k^\gamma))$, at each step. The overall complexity of CF is dominated by the computation of the partial quotients.

The following table summarizes the costs of computing the partial quotients of γ that we need:

$$\begin{array}{ll}
0^{\text{th}} \text{ step} & \tilde{O}_B(d\tau \lg(q_0^\gamma) + d^2 \lg(q_0^\gamma) \lg(q_0^\gamma)) \\
1^{\text{st}} \text{ step} & \tilde{O}_B(d\tau \lg(q_1^\gamma) + d^2 \lg(q_0^\gamma q_1^\gamma) \lg(q_1^\gamma)) \\
& \left(= \tilde{O}_B(d(\tau + d \lg(q_0^\gamma)) \lg(q_1^\gamma) + d^2 \lg^2(q_1^\gamma)) \right) \\
2^{\text{nd}} \text{ step} & \tilde{O}_B(d\tau \lg(q_2^\gamma) + d^2 \lg(q_0^\gamma q_1^\gamma q_2^\gamma) \lg(q_2^\gamma)) \\
& \vdots \\
m_\gamma^{\text{th}} \text{ step} & \tilde{O}_B(d\tau \lg(q_m^\gamma) + d^2 \lg\left(\prod_{k=0}^m q_k^\gamma\right) \lg(q_m^\gamma))
\end{array}$$

We sum over all steps to derive the cost for isolating γ , \mathcal{C}^γ , and after applying some obvious simplifications and use Lem. 6 we get

$$\begin{aligned}
\mathcal{C}^\gamma &= \tilde{O}_B \left(d\tau \sum_{k=0}^{m_\gamma} \lg(q_k^\gamma) + d^2 \sum_{k=0}^{m_\gamma} \lg(q_k^\gamma) \lg \prod_{j=0}^{m_\gamma} q_j^\gamma \right) = \tilde{O}_B \left(d\tau \sum_{k=0}^{m_\gamma} \lg(q_k^\gamma) + d^2 \left(\sum_{k=0}^{m_\gamma} \lg(q_k^\gamma) \right)^2 \right) \\
&= \tilde{O}_B \left(d\tau (\lg(q_0^\gamma) - \lg \Delta_\gamma) + d^2 (\lg^2(q_0^\gamma) + \lg^2 \Delta_\gamma) \right).
\end{aligned}$$

To derive the overall complexity, \mathcal{C} , we sum over all the roots that CF tries to isolate and we use Lem. 6 and Th. 4. Then

$$\begin{aligned}
\mathcal{C} &= \sum_\gamma \mathcal{C}^\gamma \\
&= \tilde{O}_B \left(d\tau \sum_\gamma \lg(q_0^\gamma) - d\tau \sum_\gamma \lg \Delta_\gamma + d^2 \sum_\gamma \lg^2(q_0^\gamma) + d^2 \sum_\gamma \lg^2 \Delta_\gamma \right) \\
&= \tilde{O}_B \left(d\tau \sum_\gamma \lg(q_0^\gamma) - d\tau \sum_\gamma \lg \Delta_\gamma + d^2 (\sum_\gamma \lg(q_0^\gamma))^2 + d^2 (\sum_\gamma \lg \Delta_\gamma)^2 \right) \\
&= \tilde{O}_B(d^4 \tau^2).
\end{aligned} \tag{4}$$

In the previous equation it is possible to write $\sum_\gamma \lg^2 \Delta_\gamma \leq (\sum_\gamma \lg \Delta_\gamma)^2$ because $\Delta_\gamma < 1$, and hence $\lg \Delta_\gamma < 0$, for all γ that are involved in the sum. For roots with $\Delta_\gamma \geq 1$ the algorithm isolates them without computing any of their partial quotients, with the exception of q_0^γ .

The previous discussion leads to the following theorem.

Theorem 7. *Let $A \in \mathbb{Z}[x]$, where $\deg(A) = d$ and $\mathcal{L}(A) = \tau$. The worst case complexity of isolating the real roots of A using the CF is $\tilde{O}_B(d^4 \tau^2)$.*

Remark 8. *In [33] the isolation process runs for $m_\gamma + 1$ steps, thus computes one more partial quotient for each root. However, for this partial quotient inequality (3) does not apply. We fail to see the necessity of this extra step. Nevertheless, the computation of additional partial quotients do not affect the overall complexity of the algorithm, since $\sum_\gamma \lg q_{m_\gamma+1}^\gamma = \tilde{O}(d^2 \tau)$.*

Acknowledgment

The author is grateful to Victor Pan and the anonymous referees for various constructive comments and remarks that improved the presentation of the paper.

The author is partially supported by an individual postdoctoral grant from the Danish Agency for Science, Technology and Innovation, and also acknowledges support from the Danish National Research Foundation and the National Science Foundation of China (under grant 61061130540) for the Sino-Danish Center for the Theory of Interactive Computation, within which part of this work was performed, and from the EXACTA grant of the National Science Foundation of China (NSFC 60911130369) and the French National Research Agency (ANR-09-BLAN-0371-01). Part of this work was performed while the author was with Aarhus University, Denmark.

Algorithm 1: CF(A, M)

```

Input:  $A \in \mathbb{Z}[X], M(X) = \frac{kX+l}{mX+n}, k, l, m, n \in \mathbb{Z}$ 
Output: A list of isolating intervals
Data: Initially  $M(X) = X$ , i.e.  $k = n = 1$  and  $l = m = 0$ 

1 if  $A(0) = 0$  then
2   OUTPUT Interval(  $M(0), M(0)$  );
3    $A \leftarrow A(X)/X$ ;
4   CF( $A, M$ );
5  $V \leftarrow \text{Var}(A)$ ;
6 if  $V = 0$  then RETURN;
7 if  $V = 1$  then
8   OUTPUT Interval(  $M(0), M(\infty)$  );
9   RETURN;

10  $b \leftarrow \text{PLB}(A)$  // PLB  $\equiv$  PositiveLowerBound ;
11 if  $b \geq 1$  then  $A_b \leftarrow A(b + X), M \leftarrow M(b + X)$  ;
12  $A_1 \leftarrow A_b(1 + X), M_1 \leftarrow M(1 + X)$  ;
13 CF( $A_1, M_1$ ) // Looking for real roots in  $(1, +\infty)$ ;
14  $A_2 \leftarrow A_b(\frac{1}{1+X}), M_2 \leftarrow M(\frac{1}{1+X})$  ;
15 CF( $A_2, M_2$ ) // Looking for real roots in  $(0, 1)$  ;
16 RETURN;
```

References

[1] A. Akritas. An implementation of Vincent's theorem. *Numerische Mathematik*, 36:53–62, 1980.

[2] A. Akritas. There is no "Uspensky's method". Extended Abstract. In *Proc. Symp. on Symbolic and Algebraic Computation*, pages 88–90, Waterloo, Ontario, Canada, 1986.

[3] A. Akritas. *Elements of Computer Algebra with Applications*. J. Wiley & Sons, New York, 1989.

[4] A. Akritas, W. Strzeboński, and P. S. Vigklas. Implementations of a New Theorem for Computing Bounds for Positive Roots of Polynomials. *Computing*, 78:355–367, 2006.

[5] A. Alesina and M. Galuzzi. A new proof of Vincent's theorem. *L'Enseignement Mathématique*, 44:219–256, 1998.

- [6] E. Bombieri and A. van der Poorten. Continued fractions of algebraic numbers. In *Computational algebra and number theory (Sydney, 1992)*, pages 137–152. Kluwer Acad. Publ., Dordrecht, 1995.
- [7] G. Collins and R. Loos. Real zeros of polynomials. In B. Buchberger, G. Collins, and R. Loos, editors, *Computer Algebra: Symbolic and Algebraic Computation*, pages 83–94. Springer-Verlag, Wien, 2nd edition, 1982.
- [8] J. H. Davenport. Cylindrical algebraic decomposition. Technical Report 88–10, School of Mathematical Sciences, University of Bath, England, available at: <http://www.bath.ac.uk/masjhd/>, 1988.
- [9] Z. Du, V. Sharma, and C. K. Yap. Amortized bound for root isolation via Sturm sequences. In D. Wang and L. Zhi, editors, *Int. Workshop on Symbolic Numeric Computing*, pages 113–129, School of Science, Beihang University, Beijing, China, 2005. Birkhauser.
- [10] A. Eigenwillig, V. Sharma, and C. K. Yap. Almost tight recursion tree bounds for the Descartes method. In *Proc. Annual ACM ISSAC*, pages 71–78, New York, USA, 2006.
- [11] I. Z. Emiris, A. Galligo, and E. P. Tsigaridas. Random polynomials and expected complexity of bisection methods for real solving. In S. Watt, editor, *Proc. 35th ACM Int'l Symp. on Symbolic & Algebraic Comp. (ISSAC)*, pages 235–242, Munich, Germany, July 2010. ACM.
- [12] I. Z. Emiris, B. Mourrain, and E. P. Tsigaridas. Real Algebraic Numbers: Complexity Analysis and Experimentation. In P. Hertling, C. Hoffmann, W. Luther, and N. Revol, editors, *Reliable Implementations of Real Number Algorithms: Theory and Practice*, volume 5045 of LNCS, pages 57–82. Springer Verlag, 2008. (also available in www.inria.fr/rrrt/rr-5897.html).
- [13] I. Z. Emiris, V. Y. Pan, and E. P. Tsigaridas. Algebraic and numerical algorithms. In T. Gonzalez, editor, *Computing Handbook Set - Computer Science*, volume I, chapter (In print). CRC Press Inc., Boca Raton, Florida, 3rd edition, 2012.
- [14] H. Hong. Bounds for absolute positiveness of multivariate polynomials. *J. of Symbolic Computation*, 25(5):571–585, May 1998.
- [15] J. R. Johnson. *Algorithms for Polynomial Real Root Isolation*. PhD thesis, The Ohio State University, 1991.
- [16] M. Kerber and M. Sagraloff. A worst-case bound for topology computation of algebraic curves. *J. Symb. Comput.*, 47(3):239–258, 2012.
- [17] W. Krandick. Isolierung reeller Nullstellen von Polynomen. In J. Herzberger, editor, *Wissenschaftliches Rechnen*, pages 105–154. Akademie-Verlag, Berlin, 1995.
- [18] W. Krandick and K. Mehlhorn. New bounds for the Descartes method. *JSC*, 41(1):49–66, Jan 2006.
- [19] S. Kwek and K. Mehlhorn. Optimal search for rationals. *Information Processing Letters*, 86(1):23–26, 2003.

- [20] K. Mehlhorn and S. Ray. Faster algorithms for computing Hong’s bound on absolute positiveness. *J. Symbolic Computation*, 45(6):677 – 683, 2010.
- [21] K. Mehlhorn and M. Sagraloff. A deterministic algorithm for isolating real roots of a real polynomial. *J. Symbolic Computation*, 46(1):70–90, 2011.
- [22] M. Mignotte. *Mathematics for Computer Algebra*. Springer-Verlag, New York, 1991.
- [23] C. Neff and J. Reif. An $o(n^{1+\epsilon} \log b)$ algorithm for the complex root problem. In *Proc. IEEE Symp. Foundations of Computer Science*, pages 540–547, 1994.
- [24] V. Pan. Solving a polynomial equation: Some history and recent progress. *SIAM Rev.*, 39(2):187–220, 1997.
- [25] V. Pan. Solving polynomials with computers. *American Scientist*, 86:62–69, Jan-Feb 1998.
- [26] V. Pan. Univariate polynomials: Nearly optimal algorithms for numerical factorization and rootfinding. *J. Symbolic Computation*, 33(5):701–733, 2002.
- [27] V. Pan, B. Murphy, R. Rosholt, G. Qian, and Y. Tang. Real root-finding. *Proc. of the 2007 Int. Workshop on Symbolic-Numeric Computation (SNC)*, pages 161–169, 2007.
- [28] F. Rouillier and Z. Zimmermann. Efficient isolation of polynomial’s real roots. *J. of Computational and Applied Mathematics*, 162(1):33–50, 2004.
- [29] M. Sagraloff. On the complexity of real root isolation. *CoRR*, abs/1011.0344v1, 2010.
- [30] M. Sagraloff. When Newton meets Descartes: A Simple and Fast Algorithm to Isolate the Real Roots of a Polynomial. *CoRR*, abs/1109.6279, 2011.
- [31] A. Schönhage. The fundamental theorem of algebra in terms of computational complexity. Manuscript. Univ. of Tübingen, Germany, 1982. URL: <http://www.iai.uni-bonn.de/~schoe/fdthmrep.ps.gz>.
- [32] A. Schönhage. Equation solving in terms of computational complexity. In *Proc. Int. Congress of Mathematics*, volume 1, pages 131–153, Berkeley, 1986.
- [33] V. Sharma. Complexity of real root isolation using continued fractions. *Theor. Comput. Sci.*, 409(2):292–310, 2008.
- [34] E. P. Tsigaridas. Improved complexity bounds for real root isolation using Continued Fractions. In S. Ratschan, editor, *Proc. 4th Int’l Conf. on Mathematical Aspects of Computer Information Sciences (MACIS)*, pages 226–237, Beijing, China, Oct 2011.
- [35] E. P. Tsigaridas and I. Z. Emiris. Univariate polynomial real root isolation: Continued fractions revisited. In Y. Azar and T. Erlebach, editors, *Proc. 14th European Symp. of Algorithms (ESA)*, volume 4168 of LNCS, pages 817–828, Zurich, Switzerland, 2006. Springer Verlag.
- [36] E. P. Tsigaridas and I. Z. Emiris. On the complexity of real root isolation using Continued Fractions. *Theor. Comput. Sci.*, 392:158–173, 2008.
- [37] J. V. Uspensky. *Theory of Equations*. McGraw-Hill, 1948.

- [38] A. van der Poorten. An introduction to continued fractions. In *Diophantine analysis*, pages 99–138. Cambridge University Press, 1986.
- [39] A. J. H. Vincent. Sur la résolution des équations numériques. *J. Math. Pures Appl.*, 1:341–372, 1836.
- [40] J. von zur Gathen and J. Gerhard. Fast Algorithms for Taylor Shifts and Certain Difference Equations. In *Proc. Annual ACM ISSAC*, pages 40–47, 1997.
- [41] C. Yap. *Fundamental Problems of Algorithmic Algebra*. Oxford University Press, New York, 2000.