On the Various Bisection Methods Derived from Vincent’s Theorem

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Dedicated to Professors Alberto Alesina and Massimo Galuzzi.¹

Abstract: In 2000 A. Alesina and M. Galuzzi presented Vincent’s theorem “from a modern point of view” along with two new bisection methods derived from it, B and C. Their profound understanding of Vincent’s theorem is responsible for simplicity — the characteristic property of these two methods. In this paper we compare the performance of these two new bisection methods — i.e. the time they take, as well as the number of intervals they examine in order to isolate the real roots of polynomials — against that of the well-known Vincent-Collins-Akritas method, which is the first bisection method derived from Vincent’s theorem back in 1976. Experimental results indicate that REL, the fastest implementation of the Vincent-Collins-Akritas method, is still the fastest of the three bisection methods, but the number of intervals it examines is almost the same as that of B. Therefore, further research on speeding up B while preserving its simplicity looks promising.

Key Words: Vincent’s theorem, real root isolation method, bisection method, continued fraction method, Descartes’ method, modified Uspensky’s method

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1 Introduction

We begin with a review of Descartes’ rule of signs [15].

Consider the polynomial $p(x) \in \mathbb{R}[x]$, $p(x) = a_n x^n + \cdots + a_1 x + a_0$ and let $\text{var}(p)$ represent the number of sign variations or changes (positive to negative and vice-versa) in the sequence of coefficients $a_n, a_{n-1}, \ldots, a_0$.

**Descartes’ rule of signs:** The number $\varrho_+(p)$ of real roots — multiplicities counted — of the polynomial $p(x) \in \mathbb{R}[x]$ in the open interval $]0, +\infty[$ is bounded above by $\text{var}(p)$; that is, we have $\text{var}(p) \geq \varrho_+(p)$.

According to Descartes’ rule of signs if $\text{var}(p) = 0$ it follows that $\varrho_+(p) = 0$. Additionally, according to Descartes’ rule of signs, the mean value theorem and the fact that the polynomial functions are continuous, if $\text{var}(p) = 1$ it follows that $\varrho_+(p) = 1$.

¹ For presenting Vincent’s theorem in their own, unique way!
Therefore, Descartes’ rule of signs yields the \textit{exact} number of positive roots \textit{only} in the two special cases mentioned above\textsuperscript{2}.

These two special cases of Descartes’ rule are used in Vincent’s theorem of 1836, [28], which we present in a way, due to Alessina and Galuzzi [13].

\textbf{Theorem 1.} (Vincent’s theorem — “bisection” version) Let \( f(z) \) be a real polynomial of degree \( n \), which has only simple roots. It is possible to determine a positive quantity \( \delta \) so that for every pair of positive real numbers \( a, b \) with \( |b-a| < \delta \), every transformed polynomial of the form

\[ \phi(z) = (1 + z)^n f\left(\frac{a + bz}{1 + z}\right) \]

has exactly 0 or 1 variations. The second case is possible if and only if \( f(z) \) has a simple root within \([a, b]\).

We call this the \textit{bisection} version of Vincent’s theorem, since all three bisection methods studied below are derived from it; see also [11], [12] and [21]. Also note that throughout this paper we are interested in polynomials with rational coefficients; see also [20], [23].

Moreover, the Vincent-Akritas-Strzeboński (VAS) continued fractions method is also derived from Theorem 1, since the Möbius transformation \( M(z) = \frac{a + bz}{1 + z} \), where \( a, b \in \mathbb{Q} \), is equivalent to a continued fraction of the form

\[
\alpha_1 + \frac{1}{\alpha_2 + \frac{1}{\alpha_3 + \frac{1}{\ddots + \frac{1}{\alpha_\ell}}}}
\]

where \( \alpha_1 \geq 0 \) is an arbitrary non negative integer and \( \alpha_2, \alpha_3, \ldots, \alpha_\ell \) are arbitrary positive integers, \( \alpha_i > 0 \), \( i > 1 \), [1], [2], [3], [4], [14].

It is well known, [7], [8], [9], [10], [24], and [26], that the VAS continued fractions method is, so far, the fastest method for the isolation of the real roots of polynomials; however, no data exists on the number of intervals it examines during the isolation process. This is achieved in this paper, where the VAS continued fractions method is used as a benchmark in the empirical results presented in the sequel.

The rest of the paper is structured as follows:

In Section 2 we present the three bisection methods derived from Vincent’s theorem; to wit,

- the first bisection method: Vincent-Collins-Akritas (VCA), [15], developed in 1976 by Collins and Akritas [16],

\textsuperscript{2} These two special cases were known to Cardano; in other words, what Descartes did was to generalize “Cardano’s \textit{special} rule of signs”. This detail is mentioned in [5].
– the second bisection method: B, suggested by Alesina and Galuzzi [13], and
– the third bisection method: C, suggested by Saeli [13].

In Section 3 we present experimental data comparing the performance of the
three bisection methods mentioned above juxtaposing it with that of the (VAS)
continued fractions method.

2 The Three Bisection Methods Derived from Vincent’s Theorem

The fact that bisection methods can be derived from Vincent’s theorem is missing
from major works such as ([29], pp. 470–478) and almost every paper on the
subject; to our knowledge, it appears only in [6] and the papers by Alesina and
Galuzzi [11], [13].

2.1 The First Bisection Method: Vincent-Collins-Akritas (VCA)

This method seems to be the most “complicated” of the three. It was originally
presented in a way that obscured its relation to Vincent’s theorem. Due to that
obfuscation it was originally called “modified Uspensky’s method” and recently
“Descartes’ method” ([19], [18], [17], [25]), which is totally misleading. Akritas
set the record straight, [6], by presenting the algorithm in a way that reveals
its relation to Vincent’s theorem, justifying thus the name “Vincent-Collins-
Akritas” given to it in France, [15].

A brief description of the VCA bisection method is presented below according
to [6]; see also [27]. However, we first need the following definition:

**Uspensky’s test:** The number \( \varrho_0(x) \) of real roots in the open interval \( ]0, 1[ \)
— multiplicities counted — of the polynomial \( p(x) \in \mathbb{R}[x] \) is bounded above by
\( \text{var}_{01}(p) \), where

\[
\text{var}_{01}(p) = \text{var}((x + 1)^{\text{deg}(p)} p \left( \frac{1}{x + 1} \right)), \tag{1}
\]

and we have \( \text{var}_{01}(p) \geq \varrho_0(x) \).

As in the case of Descartes’ rule of signs if \( \text{var}_{01}(p) = 0 \) it follows that
\( \varrho_0(x) = 0 \) and if \( \text{var}_{01}(p) = 1 \) it follows that \( \varrho_0(x) = 1 \).

Therefore, Uspensky’s test yields the exact number of positive roots only
in the two special cases mentioned above; to wit, whenever \( \text{var}_{01}(p) = 0 \) or
\( \text{var}_{01}(p) = 1 \).

Please note in equation (1) that, after the substitution \( x \leftarrow \frac{1}{x+1} \), the posi-
tive roots of \( p(x) \) that were in the interval \( ]0, 1[ \) are now in \( ]0, +\infty[ \), in which
case Descartes’ rule of signs can be applied.
Finally, we note that Uspensky’s test is a special instance of the powerful “Vincent’s test”, which is based on Theorem 1, applies to any interval \([a, b]\) and is described in Section 2.2.

We are now ready for the \textsc{VCA} bisection method.

Let \(p(x)\) be the polynomial whose roots we want to isolate and let \(ub\) be an upper bound on the values of its positive roots. Then all the positive roots of \(p(ub \cdot x)\) lie in the interval \([0, 1]\) and the \textsc{VCA} method isolates them by repeatedly bisecting the interval \([0, 1]\), while using in the process Uspensky’s test to make inferences about the number of positive roots certain transformed polynomials have in the interval \([0, 1]\). Finally, the isolating intervals of the roots of \(p(x)\) are easily computed from the bijection:

\[
\alpha_{[0, ub]} = a + \alpha_{[0, 1]}(b - a),
\]

that exists between the roots \(\alpha_{[0, 1]} \in [0, 1]\) of the transformed polynomial \(p(ub \cdot x)\) and the roots \(\alpha_{[0, ub]} \in [a, b] = [0, ub]\) of the original polynomial \(p(x)\).

Below is a recursive description of the \textsc{VCA} bisection method as was originally presented by Collins and Akritas:

\begin{algorithm}
\textbf{Input}: A univariate, square-free polynomial \(p(ub \cdot x) \in \mathbb{Z}[x], p(0) \neq 0\), and the open interval \([a, b] = [0, ub]\), where \(ub\) is an upper bound on the values of the positive roots of \(p(x)\). (The positive roots of \(p(ub \cdot x)\) are all in the open interval \([0, 1]\).)

\textbf{Output}: A list of isolating intervals of the positive roots of \(p(x)\) \(\forall [a, b) \ni \alpha)\). \(\varphi\)

\begin{enumerate}
\item \(\varphi\) -- the number of sign changes of \((x + 1)\deg(p(ub \cdot x));
\item if \(\varphi = 0\) then \textbf{RETURN} \(\emptyset\);
\item if \(\varphi = 1\) then \textbf{RETURN} \([a, b]\);
\item \(p_{\frac{1}{2}} \leftarrow -2^{\deg(p)}(\frac{1}{2})\) \(\text{// look for real roots in } [0, \frac{1}{2}]\);
\item \(m \leftarrow \frac{a + b}{2}\) \(\text{// is } \frac{1}{2} \text{ a root?}\);
\item \(p_{\frac{1}{2}} \leftarrow -2^{\deg(p)}(\frac{1}{2})\) \(\text{// look for real roots in } \left[\frac{1}{2}, 1\right]\);
\item if \(p(\frac{1}{2}) \neq 0\) then \textbf{RETURN} \textsc{VCA}(\(p_{\frac{1}{2}}, [a, m]\) \cup \textsc{VCA}(\(p_{\frac{1}{2}}, [m, b]\))\)
\item else \textbf{RETURN} \textsc{VCA}(\(p_{\frac{1}{2}}, [a, m]\) \cup \{[m, m]\} \cup \textsc{VCA}(\(p_{\frac{1}{2}}, [m, b]\))\)
\end{enumerate}

\textbf{Algorithm 1}: The original version of the \textsc{VCA}(\(p, [a, b]\)) “bisection” algorithm, where the second argument is the open interval \([a, b]\) associated with \(p(x)\). The isolating intervals of the roots of \(p(x)\) are computed directly, without using bijection (2).

To obtain the isolating intervals of the positive roots of \(p(x)\) we could have also used the interval \([a, b] = [0, 1]\) along with bijection (2). An excellent discussion of this algorithm can be found in [15]. Please note the following:

- Uspensky’s test is a crucial component of the \textsc{VCA}(\(p, [a, b]\)) bisection algo-
The substitutions in lines 4 and 6 are performed only on the polynomial \( p(x) \), whereas at the same time — in line 5 — the interval \([a, b]\) is divided into two equal parts \([a, m]\) and \([m, b]\), to be used in line 8 (or 10).

To isolate the real roots of \( p(x) \) in the open interval \((0, 1)\) we proceed as follows:

- we first isolate the real roots in the interval \((0, \frac{1}{2})\) — lines 4 and 8 (or 10),
- we then deal with the case where \( \frac{1}{2} \) is a root of \( p(x) \) — lines 5, 7 and 10,
- and, finally, we isolate the real roots in the interval \([\frac{1}{2}, 1]\) — lines 6 and 8 (or 10).

The isolating intervals are directly obtained from line 3 — except for those roots that happen to coincide with the midpoint of an interval that gets bisected, in which case they are computed in lines 5 and 10.

Algorithm 1 does not make clear the relation of the VCA bisection method with Vincent’s theorem. That relation is revealed if instead of the interval \([a, b]\) we associate with the polynomial \( p(x) \) the Möbius transformation \( M(x) = ub : x \) — or \( M(x) = x \) if we use bijection (2). For details see [6].

Please note that the fastest implementation of the VCA bisection method, \texttt{REL}, is due to Rouillier and Zimmermann, [22].

### 2.2 The Second Bisection Method: 8

This method is a direct implementation of Theorem 1. However, we first need the following definition, which is also used in Section 2.3:

**Vincent’s test:** If \( a \geq 0 \) and \( b > a \) then the number \( g_{ab}(p) \) of real roots in the open interval \([a, b]\), — multiplicities counted — of the polynomial \( p(x) \in \mathbb{R}[x] \) is bounded above by \( \text{var}_{ab}(p) \), where

\[
\text{var}_{ab}(p) = \text{var}((1 + x)^{\deg(p)} p\left(\frac{a + bx}{1 + x}\right)),
\]

and we have \( \text{var}_{ab}(p) = \text{var}_{ba}(p) \geq g_{ab}(p) \).

Vincent’s test is a direct consequence of Theorem 1, presented by Alesina and Galuzzi [13]. It is a very powerful test and can be applied in all cases — including the case \([a, b]=[1, 0]\), from which we obtain Uspensky’s test\(^3\).

\(^3\) By comparison, Uspensky’s test in Section 2.1, is rather weak as it applies only in the case \([a, b]=[0, 1]\).
As in the case of Descartes’ rule of signs if \( \text{var}_{ab}(p) = 0 \) it follows that \( \varrho_{ab}(p) = 0 \) and if \( \text{var}_{ab}(p) = 1 \) it follows that \( \varrho_{ab}(p) = 1 \).

Therefore, Vincent’s test yields the exact number of positive roots only in the two special cases mentioned above; to wit, whenever \( \text{var}_{ab}(p) = 0 \) or \( \text{var}_{ab}(p) = 1 \).

Below is a recursive description of the second bisection method derived from Vincent’s theorem; its simplicity is unsurpassed, but we pay for it by using a much more complicated test. Obviously, there is a trade off between simplicity of the method and complexity of the termination test.

The second bisection method: B

| Input: | A univariate, square-free polynomial \( p(x) \in \mathbb{Z}[x] \), \( p(0) \neq 0 \), and the open interval \([a, b] = [0, ub]\), where \( ub \) is an upper bound on the values of the positive roots of \( p(x) \). |
| Output: | A list of isolating intervals of the positive roots of \( p(x) \). |

1 \( var \leftarrow \) the number of sign changes of \((1 + x)^{\deg(p)} p(\frac{a + b}{2})\);
2 \( \text{if } var = 0 \text{ then RETURN } \emptyset \);
3 \( \text{if } var = 1 \text{ then RETURN } \{a, b\} \);
4 \( m \leftarrow \frac{a + b}{2} \) // Subdivide the interval \([a, b]\) into two equal parts;
5 \( \text{if } p(m) \neq 0 \text{ then RETURN } B(p, [a, m]) \cup B(p, [m, b]) \);
6 \( \text{else RETURN } B(p, [a, m]) \cup [m, m] \cup B(p, [m, b]) \);
7 \( \text{end} \)

Algorithm 2: The \( B(p, [a, b]) \) “bisection” algorithm, proposed by Alesina and Galuzzi [13]; the second argument is the open interval \([a, b]\), whose endpoints \( a, b \) are used in Vincent’s test in line 1. The isolating intervals of the roots of \( p(x) \) are computed directly, without using bisection (2).

Please note the following:

– Vincent’s test is a crucial component of the \( B(p, [a, b]) \) bisection algorithm — lines 1-3.

– In line 4 the interval \([a, b]\) is divided into two equal parts \([a, m]\) and \([m, b]\), to be used in lines 6 (or 8). Note that there are no polynomial transformations at all; only polynomial evaluations in line 1.

– To isolate the real roots of \( p(x) \) in the open interval \([a, b]\) we proceed as follows:
  • we first isolate the real roots in the interval \([a, \frac{a+b}{2}]\) — lines 6 (or 8),
  • we then deal with the case where \( \frac{a+b}{2} \) is a root of \( p(x) \) — lines 5, and 8,
  • and, finally, we isolate the real roots in the interval \([\frac{a+b}{2}, b]\) — lines 6 (or 8).
The isolating intervals are directly obtained from line 3 — except for those roots that happen to coincide with the midpoint of an interval that gets bisected, in which case they are computed in lines 5 and 8.

2.3 The Third Bisection Method: C

As Alesina and Galuzzi mention in their paper ([13], p. 189), it was Donato Saeli who suggested that they look at the connection between Farey sequences and Vincent’s theorem. We quote from their paper: “It is possible that Vincent’s theorem might be connected with Farey series in the same fruitful way it was connected with continued fractions.” Saeli’s proposal is evaluated in Section 3.

Recall that if $a \geq 0$ and $b, c, d > 0$ a mediant of the two fractions $\frac{a}{b} < \frac{c}{d}$ is given by $\frac{a+c}{b+d}$ and we have $\frac{a}{b} < \frac{a+c}{b+d} < \frac{c}{d}$.

A Farey series of order $N$, denoted by $\mathcal{F}_N$, is the set of all reduced fractions between 0 and 1 whose denominators are $N$ or less, arranged in increasing order, [13]. We can obtain $\mathcal{F}_N$ from $\mathcal{F}_{N-1}$ by inserting mediants whenever it is possible to do so without getting a denominator greater than $N$. We begin with $\mathcal{F}_1 = \{0, \frac{1}{1}\}$.

Instead of using Farey sequences in $]0, 1[$, along with bijection (2), what we have done with the third bisection method derived from Vincent’s theorem is to start with $]a, b[=]0, \frac{1}{1}[\rightarrow]a, \frac{1}{1}[\frac{a}{b} and keep inserting mediants until we isolate the positive roots of a polynomial.

Below is a recursive description of the third bisection method derived from Vincent’s theorem:
The third bisection method: C

\begin{center}
\begin{tabular}{|l|}
\hline
\textbf{Input}: A univariate, square-free polynomial \( p(x) \in \mathbb{Z}[x], p(0) \neq 0 , \) and the open interval \( [a, b]=[0, ub] , \) where \( ub \) is an upper bound on the values of the positive roots of \( p(x) . \)  \\
\hline
\textbf{Output}: A list of isolating intervals of the positive roots of \( p(x) . \) \\
\hline
\textbf{var} \leftarrow \text{the number of sign changes of } (1 + x)^{\deg(p)} \frac{1 + bx}{1 + x} ; \\
\textbf{1} \text{ if } \text{var} = 0 \text{ then RETURN } \emptyset ; \\
\textbf{2} \text{ if } \text{var} = 1 \text{ then RETURN } \{ [a, b] \} ; \\
\textbf{3} \text{ else } \\
\textbf{4} \text{ mf} \leftarrow \text{median of the interval } [a, b] , \text{ as in Farey sequences } ; \\
\textbf{5} \text{ if } p(\text{mf}) \neq 0 \text{ then } \\
\textbf{6} \text{ RETURN } \mathcal{C}(p, [a, \text{mf}]) \cup \mathcal{C}(p, \text{mf}, b) \\
\textbf{7} \text{ else } \\
\textbf{8} \text{ RETURN } \mathcal{C}(p, [a, \text{mf}]) \cup \{ [\text{mf}, \text{mf}] \} \cup \mathcal{C}(p, \text{mf}, b) \\
\textbf{9} \text{ end} \\
\hline
\end{tabular}
\end{center}

Algorithm 3: The \( \mathcal{C}(p, [a, b]) \) “bisection” algorithm, proposed by Donato Saeli, [13]; the second argument is the open interval \( [a, b] , \) whose endpoints \( a, b \) are used in Vincent’s test in line 1. The isolating intervals of the roots of \( p(x) \) are computed directly, without using bijection (2).

To obtain the isolating intervals of the positive roots of \( p(x) \) we could have also used the polynomial \( p(ub \cdot x) \) and the interval \( [a, b]=[0, 1] \) along with bijection (2). Please note the following:

- Vincent’s test is a crucial component of the \( \mathcal{C}(p, [a, b]) \) bisection algorithm — lines 1-3.

- In line 4 the interval \( [a, b] \) is divided — according to Farey’s sequences — into two parts \( [a, \text{mf}] \) and \( [\text{mf}, b] , \) to be used in lines 6 (or 8). Note that, again, there are no polynomial transformations at all; only polynomial evaluations in line 1.

- To isolate the real roots of \( p(x) \) in the open interval \( [a, b] \) we proceed as follows:
  - we first isolate the real roots in the interval \( [a, \text{mf}] \) — lines 6 (or 8), 
  - we then deal with the case where \( \text{mf} \) is a root of \( p(x) \) — lines 5, and 8, 
  - and, finally, we isolate the real roots in the interval \( [\text{mf}, b] \) — lines 6 (or 8).

- The isolating intervals are directly obtained from line 3 — except for those roots that happen to coincide with the midpoint of an interval that gets bisected, in which case they are computed in lines 5 and 8.

3 Empirical Results

In this section, we present some statistics using various classes of polynomials, as in [7]. We compare the performance of \texttt{REL} , the fastest implementation of
Vincent-Collins-Akritas (VCA) bisection method, [22], with the B and C bisection methods described in Sections 2.2 and 2.3, respectively; as a benchmark we use the Vincent-Akritas-Strzeboński (VAS) continued fractions method.

In Table 1, we present statistics on some special classes of polynomials regarding: (a) the number of intervals (#\(I\)) the methods use in order to isolate the real roots of the given polynomial, (b) the time in seconds (\(T(s)\)) they need for doing so, and (c) the number of the roots (#\(R\)).

In Table 2, we present statistics regarding some types of random polynomials; “rp” indicates a random polynomial with randomly generated coefficients, “rmp” indicates a monic polynomial with randomly generated coefficients; whereas “rr” denotes products of factors (x-randomly generated integer root).

### Table 1: Comparison of various root isolation statistics on special polynomials

| Polynomials | Method | Degrees 20 | | | Degrees 50 | | | Degrees 100 | |
|-------------|--------|------------|---|---|------------|---|---|-------------|
|             |        | #I \(I\) | \(T(s)\) | #R | #I \(I\) | \(T(s)\) | #R | #I \(I\) | \(T(s)\) | #R |
| Chebyshev   | VCA    | 48        | 0.000 20 | 106 | 0.024 50 | 208 | 0.236 100 | |
|             | B      | 50        | 0.320 20 | 106 | 3.440 50 | 222 | 51.88 100 | |
|             | C      | 98        | 0.336 20 | 422 | 16.49 50 | 1230| 419.4 100 | |
|             | VAS    | 38        | 0.004 20 | 90  | 0.024 50 | 176 | 0.204 100 | |
| Laguerre    | VCA    | 44        | 0.004 20 | 108 | 0.032 50 |     |     |     |     |
|             | B      | 48        | 0.388 20 | 112 | 5.548 50 |     |     |     |     |
|             | C      | 2150      | 9.305 20 | 33140| 2116 50 |     |     |     |     |
|             | VAS    | 35        | 0.000 20 | 92  | 0.028 50 |     |     |     |     |
| Wilkinson   | VCA    | 29        | 0.000 20 | 62  | 0.012 50 | 114 | 0.132 100 | |
|             | B      | 46        | 0.320 20 | 110 | 4.080 50 | 218 | 54.57 100 | |
|             | C      | 212       | 0.748 20 | 1284| 50.60 50 | 5066| 1894 100 | |
|             | VAS    | 21        | 0.000 20 | 51  | 0.000 50 | 101 | 0.028 100 | |
| Mignotte    | VCA    | 40        | 0.004 4  | 94  | 0.040 4  | 181 | 0.544 4  | |
|             | B      | 52        | 0.240 4  | 124 | 6.872 4  | 240 | 162.5 4  | |
|             | C      | 20        | 0.068 4  | 20  | 0.672 4  | 20  | 3.776 4  | |
|             | VAS    | 5         | 0.000 4  | 5   | 0.000 4  | 5   | 0.008 4  | 

From Table 1 we see that bisection method C examines the greatest number of intervals — save for the case of Mignotte polynomials, whose roots are extremely close. The number of intervals examined by VCA and B is of the same order. By contrast, of all methods VAS examines the smallest number of intervals.

With respect to time, VCA is the fastest of the three bisection methods as it examines the smallest number of intervals.
Table 2: Comparison of various root isolation statistics on random polynomials

<table>
<thead>
<tr>
<th>Polynomial</th>
<th>Method</th>
<th>Degrees 50</th>
<th>Degrees 100</th>
<th>Degrees 200</th>
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<td>#R</td>
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<td>VCA</td>
<td>58.4</td>
<td>0.002</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>63.6</td>
<td>0.346</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>101.2</td>
<td>0.422</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>VAS</td>
<td>35.6</td>
<td>0.003</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 2 confirms the observations made in Table 1.

4 Conclusion

In this paper we have presented three bisection methods derived from Vincent’s theorem for the isolation of the real roots of polynomials with rational coefficients and we have compared their performance against the Vincent-Akritas-Strzeboński (VAS) continued fractions method — the benchmark.

The three bisection methods — VCA, B and C — use either Uspensky’s or Vincent’s test:

– the more complex VCA method uses the simpler of these two tests, i.e. Uspensky’s,

whereas

– the very simple methods B and C use the more complex — and very powerful — Vincent’s test.

4 Remember that the former is a special instance of the latter.
The simplest of all termination tests is Descartes’ rule of signs, which is employed by the VAS method, the most “complex” method derived from Vincent’s theorem.

From the empirical results presented we have the following rule of thumb: the speed and “structural” complexity of the real root isolation algorithms derived from Vincent’s theorem are inversely proportional to the “structural” complexity of the “termination test” they employ.

Therefore, it is no longer a surprise that VAS is the fastest real root isolation method, whereas VCA comes second and is followed by B and C.

The fact that methods VCA and B examine approximately the same number of intervals indicates that further research on speeding up B is warranted.

References


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