NESTING POLYNORMALS IN INFINITE RADICALS

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Abstract. We consider infinite nested radicals in which the arguments are positive polynomial sequences. It is shown that the evaluation of such a nesting is always finite, and we prove necessary and sufficient conditions for the evaluation to be a finite polynomial.

1. Introduction

A famous problem posed by Ramanujan asks for the evaluation of the infinite nested radical
\[ \sqrt{1 + 2\sqrt{1 + 3\sqrt{1 + 4\sqrt{1 + \cdots}}}} \]
If we instead try to evaluate a more general expression, where we replace the increasing sequence by an arithmetic progression in \( x \), namely
\[ L(x) = \sqrt{1 + x\sqrt{1 + (x+1)\sqrt{1 + (x+2)\sqrt{1 + \cdots}}}} \]
then it can be seen that \( L(x) \) satisfies the functional equation
\[ L(x)^2 = 1 + xL(x+1) \]
The solution to this is \( L(x) = x + 1 \), giving the evaluation of Ramanujan's example correctly as 3. In fact, this numerical example was merely a special case of a more complicated identity in three variables (see the end of Section 2).

Several identities concerning infinite nested radicals may be found in [1], [2] and [3]. In [1], nested radicals involving arithmetic sequences in \( n \)-th roots are considered. The purpose of the current paper is to study the case where the radicals have two polynomials as their arguments.

Throughout this paper, we denote the natural numbers (without zero) and the real numbers by \( \mathbb{N} \) and \( \mathbb{R} \) respectively. The ring of polynomials in \( x \) with real coefficients will be specified by \( \mathbb{R}[x] \), and we note
further that any use of square roots automatically implies a positive square root. A sequence \(a_n\) of positive real numbers is called a positive polynomial sequence if there exists a polynomial \(a(x) \in \mathbb{R}[x]\) such that \(a_i = a(i)\) for all \(i \in \mathbb{N}\).

To remove the possibility of any ambiguity, we formalise the concept of evaluating an infinite nested radical

\[
\sqrt{a_1 + b_1 \sqrt{a_2 + b_2 \sqrt{a_3 + \ldots}}}
\]

to be the limit

\[
\lim_{n \to \infty} \sqrt{a_1 + b_1 \sqrt{a_2 + \ldots + b_{n-1} \sqrt{a_n + b_n}}}
\]  

(1)

where \(a_n, b_n\) are sequences of real numbers.

In Section 2, we characterise when an infinite nested radical involving polynomials from \(\mathbb{R}[x]\) has a simple closed form as another polynomial in \(\mathbb{R}[x]\). Section 3 is devoted to proving that, for all positive polynomial sequences \(a_n, b_n\), the limit in (1) exists and is finite.

2. IDENTITIES INVOLVING NESTED RADICALS

The following lemma does not require proof, being a consequence of viewing the infinite nested radical as being a limit of an infinite sequence.

**Lemma 2.1.** Let \(L(x)\), \(p(x)\), \(q(x)\) be polynomials in \(\mathbb{R}[x]\). Then

\[
L(x) = \sqrt{p(x) + q(x)\sqrt{p(x + d) + q(x + d)\sqrt{p(x + 2d) + \ldots}}}
\]

if and only if

\[
L(x) = \sqrt{p(x) + q(x)L(x + d)}
\]

An analogous statement can be made for higher-order roots, and we may further replace the ring \(\mathbb{R}[x]\) by any class of function in one or more variables. However, for the purposes of this paper we are primarily interested in polynomials in one variable.

From the above lemma, we get any number of results. More importantly, though, given a nested radical to evaluate, we can now concentrate on solving the non-linear functional equation

\[
L(x)^2 = p(x) + q(x)L(x + d)
\]

(2)

rather than on the radical itself, where \(L(x)\) is assumed to take positive values on the domain of interest.
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Given $L(x)$, $q(x)$ and $d$, we can always find a $p(x)$ that satisfies equation (2). That is, $p(x) = L(x)^2 - q(x)L(x + d)$. A more interesting problem is, given $p(x)$, $q(x)$ and $d$, to find the function $L(x)$. In particular, we want to find some $L(x)$ that is a polynomial of finite degree.

This is not always possible, as the following example shows. If we take $p(x) = 1$, $q(x) = x$ and $d = 2$, then we wish to find some $L(x)$ that satisfies

$$L(x)^2 = 1 + xL(x + 2)$$

It can be seen that the degree of $L(x)$ must be one, and moreover the linear term will be $x$. However, if we try to evaluate a constant term $a$, we run into problems:

$$(x + a)^2 = 1 + x(x + 2 + a)$$

$$ax + a^2 = 2x + 1$$

Comparing the linear coefficients gives $a = 2$, but the solution in the linear terms is $a = \pm 1$.

Our aim is to characterise when an infinite nested radical with polynomial arguments has a polynomial solution. That is, for what combinations of $p(x), q(x)$ and $d$ can we find some $L(x) \in \mathbb{R}[x]$ satisfying equation (2).

Let $\deg(f)$ denote the degree of a polynomial $f(x)$, and $[x^i]f(x)$ denote the coefficient of $x^i$ in the function $f(x)$. Then we have the following two lemmas, which both follow from equation (2):

**Lemma 2.2.** If $L(x) \in \mathbb{R}[x]$ solves equation (2) for some $p(x), q(x) \in \mathbb{R}[x]$, then $\deg(L) = \max\{\deg(p), 2\deg(q)\}$.

**Lemma 2.3.** Let $p(x), q(x)$ be polynomials in $\mathbb{R}[x]$, and let

$$F(x) = L(x)^2 - p(x) - q(x)L(x + d)$$

where $L(x) = a_kx^k + \ldots + a_0$. Then there exist $a_0, \ldots, a_k \in \mathbb{R}$ such that $L(x)$ solves equation (2) if and only if there exist $a_0, \ldots, a_k \in \mathbb{R}$ such that $[x^i]F(x) = 0$ for all $i \geq 0$.

This now allows us to find a solution to equation (2) by comparing coefficients of $F(x)$. While in the last lemma it is stated that $[x^i]F(x)$ must be zero for all $i \geq 0$, it suffices by Lemma 2.2 for this to hold only for values of $i$ not exceeding the maximum of $\deg(p)$ and $2\deg(q)$. While, for $L(x)$ of degree $k$, this could potentially involve solving up
to $2k + 1$ simultaneous polynomials in the $k + 1$ coefficients of $L(x)$, we can use the next lemma to find the solution systematically by solving only one quadratic equation (taking the positive root) and at most $k$ linear equations.

**Lemma 2.4.** Let $p(x), q(x)$ be polynomials in $\mathbb{R}[x]$, and let

$$F(x) = L(x)^2 - p(x) - q(x)L(x + d)$$

where $L(x) = a_kx^k + \ldots + a_0$, and $k = \max\{\deg(p), \deg(q)\}$. Then

(i) $[x^2k]F(x)$ is quadratic in $a_k$;
(ii) $[x^j]F(x)$ is linear in $a_{j-k}$ for all $k \leq j < 2k$; and
(iii) $[x^j]F(x)$ is independent of $a_i$ for all $i < j - k$ where $k \leq j \leq 2k$.

**Proof.** The coefficient $[x^{2k}]F(x)$ is given by

$$[x^{2k}]F(x) = ([x^k]L(x))^2 - [x^{2k}]p(x) - ([x^k]q(x))([x^k]L(x + d))$$

$$= a_k^2 - a_k[x^k]q(x) - [x^{2k}]p(x)$$

proving part (i). Similarly, the coefficient $[x^j]F(x)$, where $k \leq j < 2k$ is

$$[x^j]F(x) = \sum_{i=j-k}^{k} ([x^i]L(x))([x^{i-j}]L(x)) - [x^j]p(x)$$

$$- \sum_{i=j-k}^{k} ([x^i]q(x))([x^{i-j}]L(x + d))$$

$$= 2a_{j-k}a_k - a_{j-k}[x^k]q(x) - [x^j]p(x) + g(a_{j-k+1}, \ldots, a_k)$$

where $g(a_{j-k+1}, \ldots, a_k)$ takes care of the extra terms in the summations. This proves (ii), and (iii) follows directly from the expansions above.

We can now prove the main theorem of this section.

**Theorem 2.5.** Let $p(x), q(x)$ be polynomials of degree $s, t$ respectively in $\mathbb{R}[x]$, both with positive leading coefficients. Then there are $\max\{\frac{s}{2}, t\}$ equalities that must be satisfied by $d$ and the coefficients of $p(x), q(x)$ in order for some $L(x) \in \mathbb{R}[x]$ solving equation (2) to exist. Moreover, if these equalities are satisfied, then there is a general solution for $L(x)$ in terms of $d$ and the coefficients of $p(x), q(x)$.

**Proof.** We take $L(x), F(x)$ as in Lemma 2.4. Then, by the same lemma, we can find a positive $a_k \in \mathbb{R}$ that solves $[x^{2k}]F(x) = 0$. Further, given $a_i, \ldots, a_k$, where $i > 0$, we can find $a_{i-1}$ that solves $[x^{i+k-1}]F(x) = 0$. That is, we can find $a_0, \ldots, a_k$ that solve $[x^i]F(x) = 0$ for all $k \leq i \leq 2k$.  


Now, by Lemma 2.3, for $L(x) \in \mathbb{R}[x]$ to exist, we need $[x^i]F(x) = 0$ for all $i > 0$. Since we have this equality for $k \leq i \leq 2k$, we need the remaining $k$ equations to be satisfied. That is, $[x^i]F(x) = 0$ for $0 \leq i < k$. Hence there are $k$ constraints on $d$ and the coefficients of $p(x), q(x)$.

We complete the proof by noting that $L(x) = a_kx^k + \ldots + a_0$ solves equation (2) if and only if the above constraints are met with equality.

We illustrate the theorem with a more concrete example. If $p(x)$ and $q(x)$ are both linear, then we wish to find $L(x) \in \mathbb{R}[x]$ such that

$$L(x)^2 = (p_1x + p_0) + (q_1x + q_0)L(x + d)$$

In this case, it can be seen that $L(x)$ is of the form $a_1x + a_0$, and that in fact $a_1 = q_1$. So we have

$$(q_1x + a_0)^2 = (p_1x + p_0) + (q_1x + q_0)(q_1x + a_1d + a_0)$$

$$a_0q_1x + a_0^2 = (q_1q_0 + q_1^2d + p_1)x + (q_1q_0 + a_0q_0 + p_0)$$

By comparing the linear terms, we get $a_0 = q_0 + q_1d + \frac{p_1}{q_1}$, which on substitution into the constant terms gives

$$0 = q_1q_0p_1 + q_1^2d^2 + 2q_1^2p_1d + p_1^2 - q_1^2p_0$$

That is, the solution $L(x) \in \mathbb{R}[x]$ exists if and only if this equality is met, in which case

$$L(x) = q_1x + \left( q_0 + q_1d + \frac{p_1}{q_1} \right)$$

The identity of Ramanujan's, which we alluded to in the introduction, is

$$x + n + a = \sqrt{ax + (n + a)^2 + x\sqrt{a(x + n) + (n + a)^2} + \ldots}$$

where $p(x) = ax + (n + a)^2$, $q(x) = x$ and $d = n$. Applying the results we have just derived we find that the constraint in equation (3) is indeed satisfied, and the evaluation of the nested radical is $x + n + a$ as expected.

3. Convergence of Nested Radicals

At this point, we introduce a more compact notation for nested radicals. For two sequences $a_n, b_n$ of positive real numbers, we define the operator $R$ by

$$R_n(a_1, b_1) = \sqrt{a_1 + b_1 \sqrt{a_2 + \ldots + b_{n-1} \sqrt{a_n + b_n}}}$$
It was proved by Herschfeld ([2]) that $R^\infty_{i=1}(a_i, 1)$ converges if $a_i^{2^{-n}}$ has a finite upper limit as $n$ tends to infinity.

Let $p_n, q_n$ be positive polynomial sequences, and let the sequence $r_n$ be given by

$$r_n = R^n_{i=1}(p_i, q_i)$$

Then we wish to find whether or not $r_n$ converges. The next lemma will be of use.

**Lemma 3.1.** Let $u_n, v_n, y_n, z_n$ be sequences of positive real numbers such that $u_i \leq y_i, v_i \leq z_i$ for all $i \in \mathbb{N}$. Then for all $n \in \mathbb{N}$

$$R^n_{i=1}(u_i, u_i) \leq R^n_{i=1}(y_i, z_i)$$

**Proof.** The result is a straightforward consequence of the sequences being strictly positive. \(\square\)

**Theorem 3.2.** Let $p_n, q_n$ be positive polynomial sequences. Then the sequence $r_n = R^n_{i=1}(p_i, q_i)$ converges.

**Proof.** Let $p(x), q(x) \in \mathbb{R}[x]$ be polynomials such that $p(i) = p_i, q(i) = q_i$ for all $i \in \mathbb{N}$, and let $m \in \mathbb{N}$ be such that $2m > \deg(p), m > \deg(q) + 1$. Then let $L(x) = x^m$ and $v(x) = x^{m-1}$, and define $u(x)$ by

$$u(x) = L(x)^2 - q(x)L(x + 1) = x^{2m} + O(x^{2m-1})$$

We further define the sequences $u_n, v_n$ by $u_i = u(i), v_i = v(i)$. Then there is some $k \in \mathbb{N}$ such that $p_j \leq u_j, q_j \leq v_j$ for all $j \geq k$. Hence, by Lemmas 2.1 and 3.1, we have

$$\lim_{n \to \infty} R^n_{i=k}(p_i, q_i) \leq \lim_{n \to \infty} R^n_{i=k}(u_i, v_i)$$

$$= L(k)$$

$$= k^m$$

This provides a finite upper bound on $r_n$ by applying Lemma 3.1 again with the finite sequences $(q_1, \ldots, q_{k-1})$ and $(q_1, \ldots, q_{k-2}, k^m q_{k-1})$.

Now, there is also some $k \in \mathbb{N}$ such that $p_j + q_j > 1$ for all $j \geq k$. That is

$$R^j_{i=1}(p_i, q_i) \leq R^j_{i=1}(p_i, q_i)$$

for all $j \geq k$, and hence $r_n$ converges to some finite limit. \(\square\)
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