On the Average Height of $b$-Balanced Ordered Trees

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Abstract. An ordered tree with height $h$ is $b$-balanced if all its leaves have a level $\ell$ with $h - b \leq \ell \leq h$, where at least one leaf has a level equal to $h - b$. For large $n$, we shall compute asymptotic equivalents to the number of all $b$-balanced ordered trees with $n$ nodes and of all such trees with height $h$. Furthermore, assuming that all $b$-balanced ordered trees with $n$ nodes are equally likely, we shall determine the exact asymptotic behaviour of the average height of such a tree together with the variance.

1 Introduction

The concept of balanced trees such as AVL-trees, B-trees, or 2-3-trees is used in many types of data structures appearing in sorting and searching algorithms. Although the algorithmic importance of such trees is out of the question, only few results are known on the enumeration of such trees or on the exact average behaviour of impor-
tant parameters defined on these trees. A conspicuous general result in the relevant sense has been presented in [12] for balanced 2-3-trees with a specified number of leaves. This enumeration result also includes the counting of a variety of balanced trees such as B-trees with a specified order.

In this article we shall continue with the study of the class of 0-balanced ordered trees introduced in [5] by extending the notion ‘0-balanced’: Given an ordered tree $T$ with the set of leaves $L$, such a tree is called $b$-balanced, $b \in \mathbb{N}_0$, if

$$\max\{\ell v(x) | x \in L\} - \min\{\ell v(x) | x \in L\} = b;$$

here, the level $\ell v(x)$ of a node $x$ is equal to the number of nodes appearing on the simple path from the root to the node $x$ including the root and node $x$. Thus, an ordered tree with height $h := \max\{\ell v(x) | x \in L\}$ is $b$-balanced if all its leaves have a level $\ell$ with $h - b \leq \ell \leq h$, where at least one leaf has the level equal to $h - b$. All $b$-balanced ordered trees with less than six nodes are drawn in Figure 1. Clearly, $b + 2 \leq h < n + \delta_{b,0}$, $n \geq 2$, where $\delta_{n,k}$ denotes Kronecker’s delta. Note that all leaves appearing in a 0-balanced ordered tree have the same level. The parameter $b \in \mathbb{N}_0$ appearing in the definition of a $b$-balanced ordered tree with $n \geq 3$ nodes obviously describes the transition from all totally balanced $n$-node trees characterized by $b = 0$ to all (unbalanced) ordered trees with $n$ nodes characterized by $b \leq n - 3$.

The 0-balanced ordered trees are a fundamental constructive device in combinatorial considerations on enumerating specified nodes.
appearing in block code trees [6] or in other classes of trees [8, Remark 1]. The enumeration of various types of 0-balanced ordered trees together with an average case analysis of important parameters defined on these trees (e.g. the height; the path length; the root-degree) have been presented in [5]; aspects with respect to the generation of such trees have been discussed in [7, Section 3.8]. In the former paper, the author has been successful in proving that the number of all 0-balanced ordered trees of height $h$ is given by 

$$F_{n-2}^{(h-1)}, \; 2 \leq h \leq n,$$

where $F_n^{(p)}$ is the $p$th order Fibonacci number defined by $F_n^{(p)} = \delta_{n,p-1}$ for $0 \leq n < p$, and by $F_n^{(p)} = \sum_{1 \leq k \leq p} F_{n-k}$ for $n \geq p$ ([9, p. 77]). This result essentially reflects a one-to-one correspondence between 0-balanced ordered trees of height $h$ and the ordered partitions of the integer $n - h$ ([7, Section 3]; [9, p. 287]). Assuming that all 0-balanced ordered trees are equally likely, further detailed considerations (cf. [5]) imply that

- the number $t_0(n)$ of all 0-balanced ordered trees with $n$ nodes is asymptotically given by $t_0(n) \sim 2^{n-1} n^{-1} [1 + f(n)]$, $n \to \infty$;

- the average height $h_0(n)$ of a 0-balanced ordered tree with $n$ nodes has the asymptotic behaviour $h_0(n) \sim \log_2(n) + \frac{\gamma}{\ln(2)} + \chi(n)$ with the variance $\sigma_0^2(n) \sim \frac{\pi^2}{6\ln(2)} + \varphi(n)$, $n \to \infty$.

Here, $\gamma = 0.577215 \ldots$ is Euler’s constant and $h(n), h \in \{f, \chi, \varphi\}$, are bounded oscillating functions with a very small amplitude satisfying the equality $h(n) = h(2n)$.

In this paper we shall generalize these results to $b$-balanced ordered trees with $b \geq 1$. For large $n$, we shall first derive an asymptotic equivalent to the number of all $b$-balanced ordered trees of height $h$ with $n$ nodes (Theorem 4.1(a)). Then, assuming that all $b$-balanced ordered trees with $n$ nodes are equally likely, we shall find for fixed $b$ that

- the number $t_b(n)$ of all $b$-balanced ordered trees with $n$ nodes is asymptotically given by $t_b(n) \sim -\frac{1-r_b+2}{\ln(r_b+2)} r_b^{-n} n^{-1} [1 + \eta_0,b(n)]$, $n \to \infty$ (Theorem 4.1(b));

- the average height $h_b(n)$ of a $b$-balanced ordered tree with $n$ nodes has the asymptotic behaviour
\[ h_b(n) \sim -\frac{1}{\ln(r_b+2)} \left[ \ln(n) + \ln \left( e^{\gamma \frac{(1-r_b+2)(4r_b+2-1)}{(b+4)r_b+2}} \right) \right] + \chi_b(n) \]

with the variance \( \sigma_b^2(n) \sim \frac{1}{6\ln(r_b+2)} + \varphi_b(n), \ n \to \infty \) (Theorem 4.2).

Here, \( r_w := \left[ 4 \cos^2 \left( \frac{\pi}{w+2} \right) \right]^{-1} \) and \( h_b(n), h_b \in \{ \eta_0, \chi_b, \varphi_b \} \), are bounded oscillating functions with \( h_b(n) = h_b(r_b+2n) \) possessing a small amplitude not exceeding \( .04 \).

The general structure of this paper is as follows: In Section 2 we shall present basic enumeration results with respect to \( b \)-balanced ordered trees of height \( h \) with \( n \) nodes. It turns out that we have to focus our further considerations on a specific rational function which is discussed in Section 3. The determination of the dominant poles of this function (Subsection 3.2) requires subtle analytical investigations using some technical lemmata presented in Subsection 3.1. Exploiting all this information, we are able to compute the exact asymptotic behaviour of the TAYLOR coefficients of the rational function in discussion by standard methods (Subsection 3.3). Finally in Section 4, we shall use this result in order to prove the asymptotical relations for \( t_b(n) \) and \( h_b(n) \) pointed out above.

## 2 Basic Enumeration Results

We begin our study by reviewing some known results. Let \( a_h(n, m) \) be the number of all 0-balanced ordered trees with \( n \) nodes, \( m \) leaves and height \( h \), and let

\[ A_h(z, y) := \sum_{n \geq 0} \sum_{m \geq 0} a_h(n, m) z^n y^m \]

be the corresponding generating function. It is well known ([5]) that \( A_h(z, y) \) is explicitly given by

\[ A_h(z, y) = \frac{yz^h(1-z)}{1-z(y+1)+yz^h}, \ h \geq 1. \quad (1) \]

Now, let \( t_{b,h}(n) \) be the number of all \( n \)-node ordered trees of height less than or equal to \( h \) with leaves appearing at a level greater than or equal to \( h - b \). We obtain such a tree
by taking a 0-balanced ordered tree τ₀ of height h − b with n₀ nodes and m₀ leaves ℓᵢ, 1 ≤ i ≤ m₀, and

– by replacing the leaves ℓᵢ by ordered trees τᵢ with nᵢ nodes and height less than or equal to b + 1 such that n₀ + ∑₁≤i≤m₀ nᵢ = n.

Hence, the generating function of the numbers th,b(n) is given by

\[ T_{h,b}(z) := \sum_{n \geq 0} t_{h,b}(n) z^n = A_{h-b}(z, z^{-1}F_{b+1}(z)), \quad 0 \leq b < h, \quad (2) \]

where \( F_k(z) \) is the generating function of the number \( φ_k(n) \) of all ordered trees with \( n \) nodes and height less than or equal to \( k \). The classical paper [1] tells us that

\[ F_k(z) := \sum_{n \geq 0} φ_k(n) z^n = z \frac{p_k(z)}{p_{k+1}(z)}, \quad (3) \]

where

\[ p_k(z) := \frac{1}{2^k \epsilon(z)}[(1 + \epsilon(z))^k - (1 - \epsilon(z))^k], \quad (4) \]
\[ \epsilon(z) := \sqrt{1 - 4z}, \quad k \geq 0, \]

is the \( k \)th FIBONACCI polynomial satisfying the linear recurrence

\[ p_0(z) = 0, \quad p_1(z) = 1, \quad p_k(z) = p_{k-1}(z) - z p_{k-2}(z), \quad k \geq 2. \quad (5) \]

Now, inserting (1) and (3) into (2) and applying (5) to the denominator of the resulting expression, we obtain \( T_{h,b}(z) = G_{h+1,b+1}(z) \), where

\[ G_{h,b}(z) := \frac{z^{h-b} (1 - z) p_b(z)}{p_{b+1}(z) + z^{h-b} p_b(z)}, \quad 1 \leq b < h. \quad (6) \]

Note that \( G_{h,0}(z) = 0 \) and we set \( G_{h,b}(z) := 0 \) for \( b < 0 \). Introducing the number \( d_{h,b}(n) \) of all \( n \)-node ordered trees of height \( h \) with leaves appearing at a level greater than or equal to \( h - b \), a similar construction as presented above for the generating function \( T_{h,b}(z) \) immediately yields

\[ D_{h,b}(z) := \sum_{n \geq 0} d_{h,b}(n) z^n \]
\[ = A_{h-b}(z, z^{-1}F_{b+1}(z)) - A_{h-b}(z, z^{-1}F_b(z)) \]
\[ = T_{h,b}(z) - T_{h-1,b-1}(z) \]
\[ = G_{h+1,b+1}(z) - G_{h,b}(z), \quad 0 \leq b < h. \quad (7) \]
Table 1: The number $\ell_{h,b}(n)$ of all $b$-balanced ordered trees with $n \leq 9$ nodes and height $h$.

<table>
<thead>
<tr>
<th>$n \backslash h$</th>
<th>$b = 0$</th>
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<tbody>
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<td>1 1 1 1</td>
<td>5 2</td>
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<td>6</td>
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<td>7</td>
<td>1 1 1 1 1 1</td>
<td>26 20 7 2</td>
</tr>
<tr>
<td>8</td>
<td>1 1 1 1 1 1 1</td>
<td>55 55 7 2</td>
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<td>9</td>
<td>1 1 1 1 1 1 1 1</td>
<td>114 143 22</td>
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<td>10</td>
<td>1 1 1 1 1 1 1 1 1</td>
<td>234 363 22</td>
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<tr>
<th>$n \backslash h$</th>
<th>$b = 2$</th>
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<td>7</td>
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<td>8</td>
<td>326 166 47 11 2</td>
<td>247 77 15 2</td>
<td>97 19 2</td>
<td>21 2</td>
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<td>9</td>
<td>13 13 8 4 2 1 1</td>
<td>114 143 63 22</td>
<td>7 2</td>
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</tr>
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Obviously, the quantity $\ell_{h,b}(n) := d_{h,b}(n) - d_{h,b-1}(n)$, $0 \leq b < h$, is the number of all $n$-node ordered trees of height $h$ with leaves appearing at a level greater than or equal to $h - b$ such that at least one leaf has the level $h - b$. Hence, $\ell_{h,b}(n)$ is the number of all $b$-balanced ordered trees of height $h$ with $n$ nodes and the corresponding generating function is given by

$$L_{h,b}(z) := \sum_{n \geq 0} \ell_{h,b}(n)z^n = D_{h,b}(z) - D_{h,b-1}(z) = [G_{h+1,b+1}(z) - G_{h+1,b}(z)] - [G_{h,b}(z) - G_{h,b-1}(z)],$$

where $G_{h,b}(z)$ is explicitly given by (6). The first few values of $\ell_{h,b}(n)$ are summarized in Table 1. Clearly, since $p_0(z) = 0$, $p_1(z) = 1$ and $p_s(z) = 1 - (s - 2)z$, $2 \leq s \leq 4$, we rediscover the known result $L_{h,0}(z) = G_{h+1,1}(z) = A_h(z,1)$ (see [5]). Using (5), another straightforward computation yields the equalities $G_{h,h-2}(z) + z = G_{h,h-1}(z) = z \frac{p_{h-1}(z)}{p_h(z)} = F_{h-1}(z)$. These relations together with (8)
immediately imply the evident equality $L_{h,h-1}(z) = 0$ because a leaf
cannot appear at level one of the root. Furthermore, we find

$$\sum_{0 \leq b \leq h-2} L_{h,b}(z) \stackrel{(8)}{=} G_{h+1,h-1}(z) - G_{h,h-2}(z)$$

$$= z \frac{p_h(z)}{p_{h+1}(z)} - z \frac{p_{h-1}(z)}{p_h(z)}$$

$$\stackrel{(3)}{=} F_h(z) - F_{h-1}(z),$$

because all $b$-balanced ordered trees with $0 \leq b \leq h - 2$, are all
ordered trees of height $h$.

In summary, an inspection of (7) and (8) shows that we first
have to consider the enumerator $G_{h,b}(z), 0 \leq b < h$
more detailed in order to derive explicit asymptotical enumeration
and distribution results.

3 The Enumerator $G_{h,b}(z)$

3.1 Technical Lemmata

In this subsection we shall present some basic results on the Fi-
bonacci polynomials $p_k(z)$ introduced in (5) and on the polynomial
$P_{h,k}(z) := p_{k+3}(z) + z^{h-k} p_k(z)$ appearing in the denominator of the
enumerator $G_{h,k}(z)$ given in (6).

Lemma 3.1. Let $\alpha_w(j) := 4 \cos^2\left(\frac{\pi j}{w}\right)$ and $r_w := [\alpha_{w+2}(1)]^{-1}$,
$(w,j) \in \mathbb{N}^2$. The Fibonacci polynomials $p_k(z)$ fulfill the following
properties:

(a) The polynomial $p_k(z)$ has the $\lfloor \frac{1}{2}(k-1) \rfloor$ simple roots $r_{k-2} = [\alpha_k(1)]^{-1} < [\alpha_k(j)]^{-1} < [\alpha_k(j+1)]^{-1}, 2 \leq j < \lfloor \frac{1}{2}(k-1) \rfloor, k \geq 0.$

(b) The polynomial $p_k(z)$ has the representation

$$p_k(z) = \prod_{1 \leq j \leq \lfloor \frac{1}{2}(k-1) \rfloor} (1 - \alpha_k(j) z), \ k \geq 0.$$  

(c) The derivatives $p_k^{(s)}([4 \cos^2(v)]^{-1}), 0 \leq s \leq 3, k \geq 0$, are given
by

$$p_k^{(s)}([4 \cos^2(v)]^{-1}) = \frac{\Phi_k^{(s)}(v)}{2^{k-1} \sin^{2s+1}(v) \cos^{k-2s-1}(v)},$$
where
\[
\begin{align*}
\psi_k^{[0]}(\nu) &= \sin(k\nu), \\
\psi_k^{[1]}(\nu) &= -k \sin((k-2)\nu) + (k-2) \sin(k\nu), \\
\psi_k^{[2]}(\nu) &= k(k-1) \sin((k-4)\nu) - 2k(k-4) \sin((k-2)\nu) \\
&\quad + (k-3)(k-4) \sin(k\nu), \\
\psi_k^{[3]}(\nu) &= -k(k-1)(k-2) \sin((k-6)\nu) \\
&\quad + 3k(k-1)(k-6) \sin((k-4)\nu) \\
&\quad - 3k(k-5)(k-6) \sin((k-2)\nu) \\
&\quad + (k-4)(k-5)(k-6) \sin(k\nu).
\end{align*}
\]

(d) The polynomial \(p_k(z)\) and its derivatives take the following special values:
\[
\begin{align*}
p_k(r_{k-4}) &= -r_{k-4}^{\frac{1}{3}(k-2)}, \quad p_k(r_k) = r_k^{\frac{1}{3}(k-2)}, \\
p_k(r_{k-3}) &= -r_{k-3}^{\frac{1}{3}(k-1)}, \quad p_k(r_{k+1}) = (1-r_{k+1})r_{k+1}^{\frac{1}{3}(k-3)}, \\
p_k(r_{k-1}) &= r_{k-1}^{\frac{1}{3}(k-1)}, \\
p_k'(r_{k-4}) &= \frac{-2(k-2)}{4r_{k-4}^{2}}r_{k-4}^{\frac{1}{3}(k-2)}, \quad p_k'(r_k) = \frac{2(k-1)r_{k-1}-k}{4r_{k-1}^{2}}r_{k-1}^{\frac{1}{3}(k-3)}, \\
p_k'(r_{k-3}) &= \frac{-2(k-1)}{3r_{k-3}^{2}}r_{k-3}^{\frac{1}{3}(k-1)}, \quad p_k'(r_{k+1}) = \frac{(3k-2)r_k-k}{4r_k^{2}}r_k^{\frac{1}{3}(k-4)}, \\
p_k'(r_{k-2}) &= \frac{-k}{4r_{k-2}^{2}}r_{k-2}^{\frac{1}{3}(k-2)}, \quad p_k'(r_{k-1}) = \frac{-2(k-1)r_{k-1}^2+2(2k-1)r_{k+1}-k}{4r_{k+1}^{2}}r_{k+1}^{\frac{1}{3}(k-5)} \\
&\quad \times r_{k+1}^{\frac{1}{3}(k-1)}, \\
p_k''(r_{k-2}) &= -k \frac{2(2k-5)r_{k-2}-k-1}{4r_{k-2}^{2}}r_{k-2}^{\frac{1}{3}(k-4)}, \\
p_k''(r_{k+1}) &= -\frac{4}{4r_{k+1}^{2}}(k-3)(k-1)r_{k+1}^{2}-(13k^2-37k+12)r_{k+1}^3+k(7k-13)r_{k+1}-k(k-1) \\
&\quad \times r_{k+1}^{\frac{1}{3}(k-7)}, \\
p_k''(r_{k-2}) &= -k \frac{12(k^2-7k+11)r_{k-2}^2-(k-1)(7k-26)r_{k-2}+(k-2)(k-1)}{4r_{k-2}^{2}}r_{k-2}^{\frac{1}{3}(k-6)}r_{k-2}^{\frac{1}{3}(k-6)}.
\end{align*}
\]

(e) The polynomial \(p_k(z)\), \(k \geq 3\), is strictly monotonically decreasing in the interval \([0, r_{k-2}]\) and the inequality \(p_k(z) > 0\) holds for all \(z\) in that interval.
The polynomial $p_k(z), k \geq 5$, is strictly monotonically increasing in the interval $[r_{k+1}, r_k]$ and the inequality $p_k'(z) < 0$ holds for all $z$ in that interval.

The inequality $p_k''(z) > 0$ holds for all $z \in [r_{k+1}, r_k], k \geq 5$.

Proof: (a), (b): These relations are well known (see [1]). They reflect corresponding relationships fulfilled by the Chebyshev polynomials $U_k(z)$ of the second kind because the identity

$$p_k(z) = z^{\frac{1}{2}(k-1)}U_{k-1}(\frac{1}{2\sqrt{z}})$$

holds.

(c): The explicit expression for $p_k([4\cos^2(\nu)]^{-1})$ can be found in [1], too. It follows from (4) by setting $z := [4\cos^2(\nu)]^{-1}$ and by using Euler’s formula $e^{iz} = \cos(z) + i\sin(z)$, $i^2 = -1$. The expressions for the higher derivatives are obtained by taking successively the derivatives on both sides of the equation for $p_k([4\cos^2(\nu)]^{-1})$.

(d): Choosing $z \in \{r_s | k - 4 \leq s \leq k + 1\}$ in part (c) and applying elementary trigonometric relations as well as the identity $\cos(\frac{\pi}{k+2}) = \frac{1}{2}r_k^{-\frac{1}{2}}$, the explicit expressions for the special values can be derived by a straightforward lengthy computation.

(e): Taking the derivative on both sides of the equality presented in (b), we find

$$p_k'(z) = -\sum_{1 \leq j \leq \lfloor \frac{1}{2}(k-1) \rfloor} \alpha_k(j) \prod_{1 \leq \lambda \leq \lfloor \frac{1}{2}(k-1) \rfloor, \lambda \neq j} (1 - \alpha_k(\lambda) z).$$

For $z \in [0, r_{k-2}]$, we have $1 - \alpha_k(\lambda) z > 1 - \frac{\alpha_k(\lambda)}{\alpha_k(1)} > 0$ (resp. $= 0$) if $\lambda \geq 2$ (resp. $\lambda = 1$). Hence, $p_k'(z) < 0$ for $0 \leq z < r_{k-2}$, and $p_k(z)$ is strictly monotonically decreasing in $[0, r_{k-2}]$. Therefore, we have $1 \geq p_k(0) \geq p_k(z) > p_k(r_{k-2}) = 0$.

(f), (g): First, we shall show that $p_k''(z), k \geq 5$, is positive for $z \in [r_{k+1}, r_k]$. Instead of considering the function $p_k''(z)$ for $z \in [r_{k+1}, r_k]$, we change the variable and consider the function $f_k(\nu) := p_k''([4\cos^2(\nu)]^{-1})$ for $\nu \in \mathcal{I}_k := [\frac{\pi}{k+3}, \frac{\pi}{k+2}]$. Using part (c) with $s = 2$, we obtain $f_k(\nu) = p_k[2](\nu) [2^{k-1} \sin^5(\nu) \cos^{k-5}(\nu)]^{-1}$. Since $\sin(\nu)$
(resp. \( \cos(v) \)) is positive and monotonically increasing (resp. decreasing) in \( I_k \), \( k \geq 5 \), the denominator \( 2^{k-1} \sin(v) \cos^{k-5}(v) \) is positive. Using elementary trigonometric formulae, the nominator \( \vartheta_k^{[2]}(v) \) can be transformed into

\[
\vartheta_k^{[2]}(v) = -4k(k-1)\sin^2(v)\sin((k-2)v) - 12k\sin(v)\cos((k-1)v) + 12\sin(kv).
\]

Now, a moment’s reflection shows that the functions \( \sin(kv) \), \( \sin((k-2)v) \) and \( \cos((k-1)v) \) are monotonically decreasing in \( I_k \), \( k \geq 7 \), and that \( \sin(kv) \) and \( \sin((k-2)v) \) (resp. \( \cos((k-1)v) \)) are positive (resp. negative) in that interval. Therefore,

\[
\vartheta_k^{[2]}(v) > -4k(k-1)\sin^2\left(\frac{\pi}{k+2}\right)\sin\left(\frac{k-2}{k+3}\pi\right) - 12k\sin\left(\frac{\pi}{k+3}\right)\cos\left(\frac{k-1}{k+3}\pi\right) + 12\sin\left(\frac{k}{k+3}\pi\right)
\]

\[
= -4k(k-1)\sin^2\left(\frac{\pi}{k+2}\right)\sin\left(\frac{5\pi}{k+3}\right) + 12k\sin\left(\frac{\pi}{k+3}\right)
\]

\[
- 24k\sin\left(\frac{\pi}{k+3}\right)\sin^2\left(\frac{2\pi}{k+3}\right) + 12\sin\left(\frac{2\pi}{k+3}\right).
\]

Using the inequality \( \sin(x) < x - \frac{1}{6}x^3 + \frac{1}{120}x^5 \), \( x > 0 \), for the factor \( \sin\left(\frac{5\pi}{k+3}\right) \) and the inequalities \( x - \frac{1}{6}x^3 < \sin(x) < x \), \( x > 0 \), for the other factors, we further obtain by a lengthy computation

\[
\vartheta_k^{[2]}(v) > \frac{\pi}{6(k+2)^2(k+3)^2}\left(c + (k-12)\sum_{0 \leq j \leq 7} c_j k^j\right),
\]

where \( c \) and \( c_j \), \( 0 \leq j \leq 7 \), are positive constants given by

\[
c_0 = -2 (48125 \pi^6 - 8662500 \pi^4 + 652327128 \pi^2 - 5893959168),
\]
\[
c_1 = -8125 \pi^6 + 1444500 \pi^4 - 108716040 \pi^2 + 982291536,
\]
\[
c_2 = -625 \pi^6 + 120500 \pi^4 - 9051216 \pi^2 + 81811296,
\]
\[
c_3 = 4 (2375 \pi^4 - 186543 \pi^2 + 1695546),
\]
\[
c_4 = 4 (125 \pi^4 - 14472 \pi^2 + 137016),
\]
\[
c_5 = -12 (299 \pi^2 - 3360),
\]
\[
c_6 = -24 (5 \pi^2 - 96),
\]
\[
c_7 = 72,
\]
\[
c = -600 (1925 \pi^6 - 346500 \pi^4 + 26093124 \pi^2 - 235758600).
\]

Hence, \( \vartheta_k^{[2]}(v) > 0 \) for \( k \geq 12 \). For \( 5 \leq k \leq 11 \), we find directly the explicit expressions

\[
\vartheta_5^{[2]}(v) = 32\sin^5(v),
\]
\[ \vartheta_2^2 (\upsilon) = 6 \cos(2 \upsilon) + 3 \sin(5 \upsilon), \]
\[ \vartheta_2^7 (\upsilon) = 96 \left[ 4 \cos(2 \upsilon) + 3 \right] \sin(\upsilon), \]
\[ \vartheta_2^8 (\upsilon) = 128 \left[ 5 \cos(3 \upsilon) + 9 \cos(\upsilon) \right] \sin(\upsilon), \]
\[ \vartheta_2^9 (\upsilon) = 192 \left[ 5 \cos(4 \upsilon) + 10 \cos(2 \upsilon) + 6 \right] \sin(\upsilon), \]
\[ \vartheta_2^{10} (\upsilon) = 192 \left[ 7 \cos(5 \upsilon) + 15 \cos(3 \upsilon) + 20 \cos(\upsilon) \right] \sin(\upsilon), \]
\[ \vartheta_2^{11} (\upsilon) = 64 \left[ 28 \cos(6 \upsilon) + 63 \cos(4 \upsilon) + 90 \cos(2 \upsilon) + 50 \right] \sin(\upsilon). \]

Using Lemma 3.1(c) with \( s \in \{0,1\} \), we find \( \eta_{h,k}(\upsilon) = \tilde{\varphi}_{h,k}(\upsilon) \]
\[ 2k+2 \sin^3(\upsilon) \cos^k(\upsilon), \quad (10) \]

Evidently, the function \( \vartheta_2^k(\upsilon), 5 \leq k \leq 11 \), takes no negative value in the interval \( \mathcal{I}_k \) because the arguments appearing in the \( \sin \)- and \( \cos \)-functions are less than \( \frac{\pi}{2} \). It is easily verified that \( \vartheta_2^k(\upsilon) \geq \vartheta_2^k \left( \frac{\pi}{k+3} \right) > 0, 5 \leq k \leq 11. \]

In summary, we have shown that \( p_k''(z) > 0 \) for all \( z \in [r_{k+1}, r_k], k \geq 5 \). Hence, \( p_k'(z) \) is strictly monotonically increasing in that interval and we have \( p_k'(z) < p_k'(r_k) \). The value of \( p_k'(r_k) \) given in part (d) is clearly negative for \( k \geq 3. \)

**Lemma 3.2.** Let \( \alpha_w(j) := 4 \cos^2 \left( \frac{\pi j}{w} \right), r_w := [\alpha_{w+2}(1)]^{-1} \), \((w,j) \in \mathbb{N}^2\), \( p_k(z) \) be the \( \text{FIBONACCI polynomial defined in (4)} \) and \( P_{h,k}(z) := p_{k+3}(z) + z^{h-k} p_k(z). \)

(a) The polynomial \( P_{h,k}(z), h \geq k+1, k \geq 2, \) is strictly monotonically decreasing in \([r_{k+1}, r_k]\) and the inequality \( P_{h,k}'(z) < \frac{(k-1)r_{k+1}}{4r_{k+1}-1} \left[ \frac{2}{k} \right] \) holds for all \( z \) in that interval.

(b) The inequality \( P_{h,k}''(z) > 0 \) holds for all \( z \in [r_{k+1}, r_k], h \geq k+1+\delta_{k,1}, k \geq 1. \)

**Proof:** (a): Since the relations \( p_k'(z) = -(k-2), 2 \leq k \leq 4, \) (resp. \( p_k'(z) < 0 \) for \( z \in [r_{k+1}, r_k], k \geq 5 \)) hold by the definition of \( p_k(z) \) (resp. by Lemma 3.1(f)), we have \( P_{h,k}'(z) \leq \hat{\eta}_{h,k}(z) := p_{k+3}'(z) + (h-k) z^{h-k-1} p_k(z) \) for \( r_{k+1} \leq z \leq r_k \). Instead of considering the function \( \hat{\eta}_{h,k}(z) \) for \( z \in [r_{k+1}, r_k]\), we change the variable and deal with the function \( \eta_{h,k}(v) := \hat{\eta}_{h,k}(4 \cos^2(v))^{-1} \) for \( v \in \mathcal{I}_k := \left[ \frac{\pi}{4k+3}, \frac{\pi}{4k+2} \right], k \geq 2. \)

Using Lemma 3.1(c) with \( s \in \{0,1\} \), we find
\[ \eta_{h,k}(v) = \frac{\hat{\varphi}_{h,k}(v) \left[ 2k+2 \sin^3(v) \cos^k(v) \right]}{2k+2 \sin^3(v) \cos^k(v)}, \quad (10) \]
where
\[ \tilde{\varphi}_{h,k}(v) = -(k+3) \sin((k+1)v) + (k+1) \sin((k+3)v) + 4(h-k)[4 \cos^2(v)]^{-(h-k-1)} \sin(kv) \sin(2v) \sin(v). \]

Obviously, the denominator appearing in (10) is positive for \( v \in I_k \), \( k \geq 2 \), because \( 0 < v \leq \frac{\pi}{4} < \frac{\pi}{2} \). By the monotonicity of the functions \( \sin(v) \) and \( \cos(v) \) in \( I_k \), we obtain
\[ 2^{k+2} \sin^3(v) \cos^k(v) \geq 2^{k+2} \sin^3\left(\frac{\pi}{k+3}\right) \cos^k\left(\frac{\pi}{k+2}\right) = \frac{1}{2} (4r_{k+1} - 1) \frac{5}{2} r_{k+1} - \frac{1}{2} h. \quad (11) \]

Next, let us turn to the nominator \( \tilde{\varphi}_{h,k}(v) \) appearing in (10). It is easily verified that the functions \( \sin((k+1)v) \) and \( \sin((k+3)v) \), \( k \geq 2 \), and \( \sin(kv), k \geq 3 \), are monotonically decreasing in \( I_k \); the functions \( \sin(v) \), \( \sin(2v) \) and \( \cos^{-2}(v) \) are monotonically increasing in \( I_k \). Hence, we obtain
\[ \tilde{\varphi}_{h,2}(v) \leq -5 \sin\left(\frac{3\pi}{4}\right) + 4(h-2)[4 \cos^2\left(\frac{\pi}{4}\right)]^{-(h-3)} \sin^2\left(\frac{\pi}{4}\right) \sin\left(\frac{\pi}{4}\right) = \frac{1}{\sqrt{2}} \left( -5 + rac{h-3}{2h-3} \right) \leq -\frac{1}{\sqrt{2}} < -\sin\left(\frac{\pi}{3}\right), \quad (12) \]
and for \( k \geq 3 \)
\[ \tilde{\varphi}_{h,k}(v) \leq -(k+3) \sin\left(\frac{k+1}{k+2}\pi\right) + 4(h-k)[4 \cos^2\left(\frac{\pi}{k+2}\right)]^{-(h-k-1)} \sin\left(\frac{k}{k+3}\pi\right) \sin\left(\frac{2\pi}{k+2}\right) \sin\left(\frac{\pi}{k+2}\right) = \sin\left(\frac{\pi}{k+2}\right) \left[ - (k+3) + 4(h-k) \sin\left(\frac{3\pi}{k+3}\right) \sin\left(\frac{2\pi}{k+2}\right) \right]^{h-k-1} \leq \frac{1}{1} < 1 < (k-1) \sin\left(\frac{\pi}{k+2}\right), \quad (13) \]

because \( (h-k)r_{h-k}^h \leq r_k \) for \( h \geq k+1 \). Now, combining (10), (11), (12) and (13), we find the inequality stated in part (a) of the lemma implying that \( P_{h,k}(z) \) is strictly monotonically decreasing in the interval \([r_{k+1}, r_k]\).

(b) Using additionally Lemma 3.1(g), the stated inequality can be proved in a similar way. The details are left to the reader. \( \square \)

**Lemma 3.3.** Let \( \alpha_w(j) := 4 \cos^2\left(\frac{\pi j}{w}\right), \ r_w := |\alpha_{w+2}(1)|^{-1}, \ (w,j) \in \mathbb{N}^2 \) and \( \chi(x,\varphi) := 1 + x^2 - 2x \cos(\varphi), \ 0 \leq \varphi < 2\pi \). We have:
(a) \( \chi(x, \varphi) = 0 \) iff \((\varphi, x) \in \{(0, 1), (\pi, -1)\} \), and \( \chi(x, \varphi) > 0 \), otherwise. Furthermore, \( \chi(x, \varphi), x > 0 \), has a minimum (resp. maximum) at \( \varphi = 0 \) (resp. \( \varphi = \pi \)) and the inequalities \( (1 - x)^2 \leq \chi(x, \varphi) \leq (1 + x)^2 \) hold.

(b) \( \chi(r_w, \alpha_{w+3}(j), \varphi) > 0 \), and \( \chi(r_w, \alpha_w(j), \varphi) > 0 \), for all \( \varphi \in [0, 2\pi] \), and all \( 1 \leq j \leq \lfloor \frac{1}{2}(w + 2) \rfloor \).

(c) Let \( q_w(j, \varphi) := \frac{\chi(r_w, \alpha_{w+3}(j), \varphi)}{\chi(r_w, \alpha_w(j), \varphi)} \). The inequality

\[
q_w(j, \varphi) := \prod_{1 \leq j \leq \lfloor \frac{1}{2}(w + 2) \rfloor} q_w(j, \varphi) > \frac{1}{4} r_w^4
\]

holds for all \( w \geq 3 \) and \( \varphi \in [0, 2\pi] \).

**Proof:** (a): An elementary discussion of the function \( \chi(x, \varphi) \) yields the established statements.

(b): Since \( j \in \mathbb{N} \), it is easily verified that \( 0 < r_w \alpha_{w+3}(j) \neq 1 \) and \( 0 < r_w \alpha_w(j) \neq 1 \) for \( 1 \leq j \leq \lfloor \frac{1}{2}(w + 2) \rfloor \). Hence, the stated inequalities follow from part (a).

(c) We have

\[
\frac{\partial}{\partial \varphi} q_w(j, \varphi) = \frac{2 r_w [\alpha_w(j) - \alpha_{w+3}(j)] [r_w^2 \alpha_w(j) \alpha_{w+3}(j) - 1]}{[1 + r_w^2] \alpha_w(j)^2 - 2 r_w \alpha_w(j) \cos(\varphi)]^2} \sin(\varphi).
\]

Thus, the function \( q_w(j, \varphi) \) has relative extreme values at \( \varphi \in \{0, \pi\} \). We find

\[
\frac{\partial^2}{\partial \varphi^2} q_w(j, \varphi) \bigg|_{\varphi=0} = \frac{2 r_w [\alpha_w(j) - \alpha_{w+3}(j)] [r_w^2 \alpha_w(j) \alpha_{w+3}(j) - 1]}{[1 - r_w \alpha_w(j)]^4}
\]

and

\[
\frac{\partial^2}{\partial \varphi^2} q_w(j, \varphi) \bigg|_{\varphi=\pi} = \frac{-2 r_w [\alpha_w(j) - \alpha_{w+3}(j)] [r_w^2 \alpha_w(j) \alpha_{w+3}(j) - 1]}{[1 + r_w \alpha_w(j)]^4}.
\]

Hence, \( q_w(j, \varphi), 1 \leq j \leq \lfloor \frac{1}{2}(w + 2) \rfloor \) has a minimum at

- \( \varphi = 0 \) iff \( \alpha_w(j) \geq \alpha_{w+3}(j) \) and \( r_w^2 \alpha_w(j) \alpha_{w+3}(j) \leq 1 \),
- \( \varphi = \pi \) iff \( \alpha_w(j) \leq \alpha_{w+3}(j) \) and \( r_w^2 \alpha_w(j) \alpha_{w+3}(j) \geq 1 \).
Now, elementary computations show, for \( w \geq 3 \) and \( 1 \leq j \leq \lfloor \frac{1}{2}(w+2) \rfloor \),
\[
\alpha_w(j) - \alpha_{w+3}(j) =
\begin{cases} 
> 0, & \text{if } w \equiv 0 \mod 2 \land j = \lfloor \frac{1}{2}(w+2) \rfloor; \\
0, & \text{if } (w, j) = (3, 2); \\
< 0, & \text{otherwise},
\end{cases}
\]
(14)
and \( r_w^2 \alpha_w(j) \alpha_{w+3}(j) < 1 \). Thus, \( q_w(j, \varphi) \), \( 1 \leq j \leq \lfloor \frac{1}{2}(w+2) \rfloor \), \( w \geq 3 \),
has a minimum at \( \varphi = \pi \) iff \( w \equiv 0 \mod 2 \land j = \lfloor \frac{1}{2}(w+2) \rfloor \), and
at \( \varphi = 0 \) otherwise with the exception of \((w, j) = (3, 2)\). Note that
\( q_3(2, \varphi) \equiv 1 \). Therefore, we obtain, for \( w \geq 3 \),
\[
f_w(\varphi) = q_w(\lfloor \frac{1}{2}(w+2) \rfloor, \varphi) \prod_{1 \leq j \leq \lfloor \frac{1}{2}w \rfloor} q_w(j, \varphi)
\geq q_w(\lfloor \frac{1}{2}(w+2) \rfloor, \pi \delta_{0,w \mod 2}) \prod_{1 \leq j \leq \lfloor \frac{1}{2}w \rfloor} q_w(j, 0)
= \left( \frac{1 + \xi_w r_w \alpha_{w+3}(\lfloor \frac{1}{2}(w+2) \rfloor)}{1 + \xi_w r_w \alpha_w(\lfloor \frac{1}{2}(w+2) \rfloor)} \right)^2 \prod_{1 \leq j \leq \lfloor \frac{1}{2}w \rfloor} \left( \frac{1 - r_w \alpha_{w+3}(j)}{1 - r_w \alpha_w(j)} \right)^2,
\]
(15)
where \( \xi_w := (-1)^{w \mod 2} \). Now, using Lemma 3.1(b), we find
\[
\prod_{1 \leq j \leq \lfloor \frac{1}{2}w \rfloor} \frac{1 - r_w \alpha_{w+3}(j)}{1 - r_w \alpha_w(j)} = \frac{1}{1 - r_w \alpha_w(\lfloor \frac{1}{2}(w+2) \rfloor)} \frac{p_{w+3}(r_w)}{p_w(r_w)}.
\]
The quotient \( \frac{p_{w+3}(r_w)}{p_w(r_w)} \) can be explicitly computed by the corresponding formulae presented in Lemma 3.1(d). We immediately find \( \frac{p_{w+3}(r_w)}{p_w(r_w)} = -r_w^2 \). Hence, the lower bound for \( f_w(\varphi) \) presented in (15) can be simplified to
\( f_w(\varphi) \geq \mu_w^2 r_w^4 \), where
\[
\mu_w := \frac{1}{1 + \xi_w r_w \alpha_w(\lfloor \frac{1}{2}(w+2) \rfloor)} \frac{1 + \xi_w r_w \alpha_{w+3}(\lfloor \frac{1}{2}(w+2) \rfloor)}{1 - r_w \alpha_{w+3}(\lfloor \frac{1}{2}(w+2) \rfloor)}.
\]
The latter factor appearing on the right-hand side is clearly equal to one for odd \( w \), and greater than one for even \( w \) because \( r_w \alpha_{w+3}(\lfloor \frac{1}{2}(w+2) \rfloor) > 0 \). Since \( 0 < r_w \alpha_w(\lfloor \frac{1}{2}(w+2) \rfloor) \leq \frac{2}{3} \), we further obtain
\( \mu_w \geq \left[ 1 + \xi_w r_w \alpha_w(\lfloor \frac{1}{2}(w+2) \rfloor) \right]^{-1} \geq \frac{3}{5} > \frac{1}{2} \). This completes the proof.
\[\square\]

**Lemma 3.4.** Let \( \alpha_w(j) := 4 \cos^2 \left( \frac{\pi j}{w} \right) \), \( r_w := |\alpha_{w+2}(1)|^{-1} \), \( (w, j) \in \mathbb{N}^2 \) and \( p_k(z) \) be the Fibonacci polynomial defined in (4). For \( |z| =
The function \( \Delta_w(z) := \frac{r^3_w - |p_{w+3}(z)|}{|p_w(z)|} \), \( w \geq 2 \), satisfies the inequality \( \Delta_w(z) \leq -\Upsilon r^2_w < 0 \), where \( \Upsilon := \frac{3}{2 \sqrt{2}} - 1 \approx .060660\ldots > 0 \).

**Proof:** By Lemma 3.1(a), the positive root of minimum modulus of the polynomial \( p_w(z) \) is at \( z = r_{w-2} > r_w \). Hence, \( \Delta_w(z) \) is well defined on the circle \( |z| = r_w \). Now, using Lemma 3.1(b) and the definition of the function \( \chi \) introduced in Lemma 3.3, we obtain for \( z := r_w e^{i \varphi}, r^2 = -1, 0 \leq \varphi < 2\pi, \)

\[
\Delta_w(z) = r^3_w - \left( \frac{p_{w+3}(z)p_{w+3}(\overline{z})}{p_w(z)p_w(\overline{z})} \right)^{\frac{1}{2}} \\
= r^3_w - \prod_{1 \leq j \leq \left\lfloor \frac{1}{2}(w+2) \right\rfloor} [\chi(r_w \alpha_{w+3}(j), \varphi)]^{\frac{1}{2}} \\
\times \prod_{1 \leq j \leq \left\lfloor \frac{1}{2}(w+2) \right\rfloor} [\chi(r_w \alpha_{w}(j), \varphi)]^{-\frac{1}{2}}.
\]

Since \( r_w \alpha_w\left(\frac{1}{2}(w-1) + 1\right) = 0 \), for even \( w \geq 2 \), we have \( \chi(r_w \alpha_w\left(\frac{1}{2}(w-1) + 1\right), \varphi) = 1 \) by Lemma 3.3(a), and therefore for \( z := r_w e^{i \varphi}, r^2 = -1, 0 \leq \varphi < 2\pi, \)

\[
\Delta_w(z) = r^3_w - [\chi(r_w \alpha_w\left(\frac{1}{2}(w+2)\right), \varphi)]^{\frac{1}{2}} \\
\times \prod_{1 \leq j \leq \left\lfloor \frac{1}{2}(w+2) \right\rfloor} \left( \frac{\chi(r_w \alpha_{w+3}(j), \varphi)}{\chi(r_w \alpha_{w}(j), \varphi)} \right)^{\frac{1}{2}}.
\]

Now, we shall successively consider the four cases \( w \in \{2, 3, 4\} \) and \( w \geq 5 \).

- Since \( w = 2 \), we immediately obtain for \( z := r_2 e^{i \varphi}, 0 \leq \varphi < 2\pi, \)

\[
\Delta_2(z) = r^3_2 - [\chi(r_2 \alpha_5(1), \varphi)]^{\frac{1}{2}} [\chi(r_2 \alpha_5(2), \varphi)]^{\frac{3}{2}} \\
= \left( \frac{r^2_2}{2} - \left[ \frac{1}{2} \left( 1 - \cos(\varphi) \right) \left( 11 - 4 \cos(\varphi) + \frac{1}{16} \right)^{\frac{1}{2}} \right] \right) \\
\leq \frac{1}{8} - \frac{1}{4} = -\frac{1}{2} r^2_2 < -\Upsilon r^2_2.
\]

- Since \( w = 3 \), we find for \( z := r_3 e^{i \varphi}, 0 \leq \varphi < 2\pi, \)

\[
\Delta_3(z) = r^3_3 - \left( \frac{\chi(r_3 \alpha_6(1), \varphi)}{\chi(r_3 \alpha_6(2), \varphi)} \right)^{\frac{1}{2}} \\
\times \prod_{1 \leq j \leq \left\lfloor \frac{1}{2}(w+2) \right\rfloor} \left( \frac{\chi(r_3 \alpha_{w+3}(j), \varphi) \chi(r_3 \alpha_{w}(j), \varphi)}{\chi(r_3 \alpha_{w+3}(j), \varphi) \chi(r_3 \alpha_{w}(j), \varphi)} \right)^{\frac{1}{2}}.
\]
\[ \Delta_4(z) = r_4^3 - \left( \frac{12}{(1 + \sqrt{5})^2} - 1 \right)^2 \left( 1 - \cos(\varphi) \right) \geq 0 \]
\[ = r_4^3 - \left( \frac{12}{(1 + \sqrt{5})^2} - 1 \right)^2 \left( 1 - \cos(\varphi) \right) \geq 0 \]
\[ \leq \frac{1}{27} - \frac{1}{9} = -\frac{2}{3} r_4^2 < -\Upsilon r_4^2. \]

Finally, let \( w \geq 5 \). Using the inequalities established in part (a) and (c) of Lemma 3.3, we find for \( z := r_w e^{i \varphi}, 0 \leq \varphi < 2\pi \),
\[ \Delta_w(z) = r_w^3 - \left( \frac{\chi(r_w \alpha_w(1), \varphi)}{\chi(r_w \alpha_w(1), \varphi)} \right)^{\frac{1}{2}} \]
\[ = r_w^3 - \left[ \frac{1}{8} + \frac{4 (1 - \cos(\varphi))}{27 (13 - 12 \cos(\varphi))} \right] \geq 0 \]
\[ \leq \frac{1}{27} - \frac{1}{9} = -\frac{2}{3} r_w^2 < -\Upsilon r_w^2. \]

It is not hard to show that \( \lambda(2w + 1) \) (resp. \( \lambda(2w) \)) is monotonically decreasing for growing \( w \geq 2 \) (resp. \( w \geq 3 \)). Since \( \lambda(5) = -\frac{1}{16} (8 - [7 - \sqrt{5}] \cos^{-2}(\frac{\pi}{7})) \approx -0.133202 \ldots < -\Upsilon \) and \( \lambda(6) = -\Upsilon \), we have \( \lambda(w) \leq \lambda(6) \) for \( w \geq 5 \).

This completes the proof. \( \square \)

### 3.2 The Dominant Poles of \( G_{h,b}(z) \)

In this subsection we shall determine the root of minimum modulus of the polynomial \( P_{h,k}(z) = p_{k+3}(z) + z^{h-k} p_k(z) \) appearing in the denominator of the enumerator \( G_{h,k}(z) \) introduced in (6).

**Theorem 3.1.** Let \( \alpha_w(j) := 4 \cos^2 \left( \frac{j \pi}{w} \right) \) and \( r_w := [\alpha_w+2(1)]^{-1} \), \((w,j) \in \mathbb{N}^2\). We have:
(a) The enumerator \( G_{h,b}(z) \) has a dominant singularity \( z_{h,b} \), for \( 1 \leq b < h, \ h \geq 3 \), which is a simple pole.

(b) The dominant singularities \( z_{h,b}, \ 1 \leq b < h, \ h \geq 3 \), satisfy the following chain of inequalities

\[
1 = r_1 > z_{h,1} > r_2 > z_{h,2} > r_3 > \ldots > r_b > z_{h,b} > r_{b+1} > \ldots > r_{h-3} > z_{h,h-3} > r_{h-2} = z_{h,h-2} = z_{h,h-1} > \frac{1}{2}.
\]

(c) The dominant singularities \( z_{h,b} \) satisfy the following chain of inequalities

\[
\begin{align*}
 r_1 &= z_{3,1} \\
r_{b-1} &= z_{b+1,b} > r_b = z_{b+2,b} & \quad \text{if } b = 1 \\
r_{b-1} &= z_{b+1,b} > r_b = z_{b+2,b} & \quad \text{if } b \geq 2
\end{align*}
\]

(d) The dominant singularity \( z_{b+3,b}, \ b \geq 1 \), satisfies the inequality

\[
z_{b+3,b} < \hat{r}_b := \left[ 4 \cos^2 \left( \frac{2\pi}{2b+3} \right) \right]^{-1} < r_b.
\]

**Proof:** (a), (b): Clearly, the inequalities \( \frac{1}{4} < r_{j-1} < r_j < r_1 = 1 \) hold for \( j \geq 2 \) by definition.

As pointed out at the end of Section 2, the enumerator \( G_{h,b}(z) \), \( b \in \{ h-1, h-2 \} \), has the representation \( G_{h,b}(z) = z \frac{p_{h-1}(z)}{p_h(z)} - \delta_{h-2,b} z \), where \( p_b(z) \) denotes a **Fibonacci** polynomial. Hence, \( G_{h,h-1}(z) \) (resp. \( G_{h,h-2}(z) \)) has a simple pole at \( z_{h,h-1} = r_{h-2} \) (resp. \( z_{h,h-2} = r_{h-2} \), \( h \geq 3 \), by Lemma 3.1(b)). Therefore, it is sufficient to restrict our further considerations to \( 1 \leq b \leq h-3, \ h \geq 4 \).

Since \( G_{h,b}(z) \) is an enumerator, the dominant singularity \( z_{h,b} \) is the positive root of minimum modulus of the polynomial \( P_{h,b}(z) := p_{h+3}(z) + z^{h-b} p_b(z) \) appearing in the denominator of (6) such that the nominator \( N_{h,b}(z) := (1 - z) z^{h-b} p_b(z) \) is unequal to zero for \( z = z_{h,b} \). Note that the polynomial \( P_{h,b}(z) \), \( b \geq 1 \), has the degree \( \max\{ \lfloor \frac{1}{2} b \rfloor + 1, h-1 - \lfloor \frac{1}{2} b \rfloor \} \).

For \( b = 1 \), i.e. \( h \geq 4 \), we obtain \( P_{h,1}(z) = 1 - 2z + z^{h-1} \). This polynomial has already been discussed in [5]. It has exactly one simple positive root \( z_{h,1} \) inside the circle \( |z| = 1 = r_1 \). Since \( z_{h,1}^{h-1} = 2z_{h,1} - 1 \), the inequality \( z_{h,1} \geq 1 \) holds. Obviously, \( N_{h,1}(z_{h,1}) = (1 - z_{h,1}) z_{h,1}^{h-1} p_1(z_{h,1}) \neq 0 \). Hence, \( G_{h,1}(z) \), \( h \geq 4 \), has a simple pole at \( z_{h,1} \) with \( r_2 < z_{h,1} < r_1 \). Note that the exact expression

\[
z_{h,1} = \sum_{j \geq 0} \frac{1}{(h-1)j+1} \binom{(h-1)j+1}{j} 2^{-(h-1)j-1}
\]
has been computed in [5].

Now, let $b \geq 2$, i.e. $h \geq 5$. Setting $\varphi_{h,b}(z) := z^{h-b} p_h(z)$ and $\psi_b(z) := p_{b+3}(z)$ and using the definition of the function $\chi$ (resp. $\Delta_w$) introduced in Lemma 3.3(a) (resp. Lemma 3.4), we can make the following computations for $z = r_b e^{i \varphi}$, $0 \leq \varphi < 2\pi$, 

$$|\psi_b(z)| = (|p_{b+3}(z)| |p_b(z)|^{\frac{1}{2}} \prod_{1 \leq j \leq \lfloor \frac{1}{2}(b+2) \rfloor} \frac{|(1 - r_b \alpha_{b+3+j}(e^{i \varphi}))(1 - r_b \alpha_{b+3+j}(e^{-i \varphi}))|^{\frac{1}{2}}}{\chi(r_b \alpha_{b+3+j}(e^{i \varphi}))}$$

$$= \chi(\alpha_{b+3+j}(e^{i \varphi}))$$

and

$$|\varphi_{h,b}(z)| - |\psi_b(z)| = |p_b(z)| \left[ \frac{|z|^{h-b}}{p_b(z)} - \frac{|p_{b+3}(z)|}{|p_b(z)|} \right] \leq r_b^3 \geq 0.$$  \hspace{1cm} (17)

Thus, the relations $\psi_b(z) \neq 0$ and $|\varphi_{h,b}(z)| < |\psi_b(z)|$ hold for $|z| = r_b$, $b \geq 2$. Hence, Rouche’s theorem applies and the polynomials $\psi_b(z)$ and $\varphi_{h,b}(z)$ are at exactly one positive simple root $\hat{\varphi}_{h,b}$ because $0 < \hat{\varphi}_{h,b} < r_b \leq r_2 < 1$, Hence, the
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The enumerator \( G_{h,b}(z) \), \( h \geq b + 3 \geq 5 \), has a simple pole at \( z_{h,b} := \hat{z}_{h,b} \) with \( r_{b+1} < z_{h,b} < r_b \).

(e) The equalities \( z_{3,1} = r_1 \) and \( z_{b+1,b} = r_{b-1}, \ b \geq 2 \), have already been verified at the beginning of the proof of the parts (a) and (b) of this lemma.

Now, assume that there is a tuple \((h, b)\), \( h \geq b + 1, \ b \geq 2 \), with \( z_{h,b} \leq z_{h+1,b} \). By part (b) of this lemma, we know that both, \( z_{h,b} \) and \( z_{h+1,b} \), lie in the interval \( ]r_{b+1}, r_b[ \subseteq \left] \frac{1}{2}, \frac{3}{2} \right[ \). Since \( p_2(z) = 1 > 0 \) and \( p_b(z_{h,b}) > 0, \ b \geq 3 \), by Lemma 3.1(e), the assumption \( \hat{z}_{h,b} := z_{h,b} = z_{h+1,b} \) immediately yields \( 0 = P_{h+1,b}(\tilde{z}_{h,b}) - P_{h,b}(\hat{z}_{h,b}) = \hat{z}_{h,b} \) \( \left( \hat{z}_{h,b} - 1 \right) p_b(\hat{z}_{h,b}) \), i.e. we have the contradiction \( \hat{z}_{h,b} \in \{0, 1\} \). Assuming that \( z_{h,b} < z_{h+1,b} \), Lemma 3.2(a) yields

\[
0 = P_{h+1,b}(z_{h+1,b}) < P_{h+1,b}(z_{h,b}) = p_{b+3}(z_{h,b}) + z_{h,b}^{h+1} p_b(z_{h,b})
< p_{b+3}(z_{h,b}) + z_{h,b}^{h+1} p_b(z_{h,b}) = P_{h,b}(z_{h,b}) = 0,
\]

which is another contradiction.

We are left with the case \( b = 1 \). Since \((h - 1) j + 1 < h j + 1 \) and \( h j - \lambda + 2 < 2 [(h - 1) j - \lambda + 2], \ 1 \leq \lambda \leq j \), we immediately obtain \( z_{h+1,1} < z_{h,1}, \ h \geq 3 \), by the explicit expression for \( z_{h,1} \) established in (16).

(d) Since \( \frac{\pi}{b+3} < \frac{2\pi}{2b+3} < \frac{\pi}{b+2}, \ b \geq 1 \), we have \( r_{b+1} < \hat{r}_b < r_b \).

First, for \( b = 1 \), we find \( P_{4,1}(z) = 1 - 2z + z^3 = (z - 1) (z + \phi) (z + \phi^{-1}) \), where \( \phi := \frac{1}{2} (1 + \sqrt{5}) \) is the ‘golden ratio’. Hence, \( z_{4,1} = \phi^{-1} = .618033 \ldots < [4 \cos^2 \left( \frac{\pi}{4} \right)]^{-1} = \hat{r}_1 \approx .643104 \ldots \).

Next, let \( b \geq 2 \). An inspection of Lemma 3.2(a) shows that \( P_{b,b}(z), \ b \geq 2, \) is strictly monotonically decreasing in \([r_{b+1}, r_b]\). Since \( z_{b+3,b} \) is the unique root of \( P_{b+3,b}(z) \) in \([r_{b+1}, r_b]\), it is sufficient to prove that \( P_{b+3,b}(\hat{r}_b) < 0 \). For this purpose we change the variable and consider the function

\[

\nu_b(v) := P_{b+3,b}([4 \cos^2(v)]^{-1})
= p_{b+3}([4 \cos^2(v)]^{-1}) + [4 \cos^2(v)]^{-3} p_b([4 \cos^2(v)]^{-1})
\]

in the interval \([\frac{\pi}{b+3}, \frac{\pi}{b+2}]\). Setting \( v := \frac{2\pi}{2b+3} \) and using Lemma 3.1(e), elementary trigonometric transformations yield \( P_{b+3,b}(\hat{r}_b) = \ldots \)
\[ \nu_b \left( \frac{2\pi}{2b+5} \right) = \frac{1}{2b+6} \cos \left( \frac{\pi}{2b+5} \right) \left( \cos^5 \left( \frac{2\pi}{2b+5} \right) + 5 \right) > 0 \]

\[ \times \left[ 4 \cos^2 \left( \frac{\pi}{2b+3} \right) - 1 \right] > 0. \]

Evidently, the latter expression is negative. This completes the proof.

\[ \square \]

**Remark 3.1.** (a) The preceding lemma presents a detailed survey of the dominant singularities \( z_{h,b} \) of the enumerators \( G_{h,b}(z) \), \( 1 \leq b < h \), \( h \geq 3 \). Arranging the values of \( z_{h,b} \) in an array, this array has the following structure:

<table>
<thead>
<tr>
<th>h ( \backslash ) b</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>\ldots</th>
<th>h</th>
<th>h - 1</th>
<th>h - 2</th>
<th>\ldots</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>b</td>
<td></td>
<td>\ldots</td>
<td></td>
<td>b</td>
<td>b</td>
<td>\ldots</td>
<td>h-1</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>\ldots</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>\ldots</td>
<td>h-2</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>\ldots</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>\ldots</td>
<td>h-3</td>
</tr>
<tr>
<td>\ldots</td>
<td></td>
<td></td>
<td></td>
<td>\ldots</td>
<td></td>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
</tr>
<tr>
<td>h</td>
<td></td>
<td></td>
<td></td>
<td>\ldots</td>
<td></td>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
<td></td>
</tr>
</tbody>
</table>

The corresponding values of \( z_{h,b} \) are given by:

- For \( b = 1 \):
  - \( z_{1,1} = r_1 \), \( z_{1,2} = r_2 \), \ldots , \( z_{1,h} = r_h \)
- For \( b = 2 \):
  - \( z_{2,1} = r_1 \), \( z_{2,2} = r_2 \), \ldots , \( z_{2,h} = r_h \)
- For \( b = 3 \):
  - \( z_{3,1} = r_1 \), \( z_{3,2} = r_2 \), \ldots , \( z_{3,h} = r_h \)
- \ldots

Where \( r_1 > r_2 > r_3 > \ldots > r_h \).
In each row (resp. column), the entries are strictly monotonically decreasing from left to right (resp. top to bottom).

(b) We are left with the concrete problem of computing an approximation of the dominant singularity \( z_{h,b} \) for \( 1 \leq b \leq h - 3 \), i.e. we have to find an approximation of the simple positive root of minimum modulus of the polynomial \( P_{h,b}(z) = p_{b+3}(z) + z^{h-b}p_{b}(z) \). This problem can essentially be solved by newton’s method, i.e. we have to consider the recurrence

\[
z_t = z_{t-1} - \frac{p_{b+3}(z_{t-1}) + z_{t-1}^{h-b}p_{b}(z_{t-1})}{p'_{b+3}(z_{t-1}) + z_{t-1}^{h-b-1}[z_{t-1}^{h-b} + z_{t-1}^{h-b-1}p_b(z_{t-1})]} , \quad t \geq 1,
\]

starting with a well chosen initial value \( z_0 \). We choose \( z_0 := r_{b+1} \) because \( p_{b+3}(r_{b+1}) = 0 \) by Lemma 3.1(a), and \( z_{b+1}^{h-b}p_b(r_{b+1}) = (1 - r_{b+1})n^{h-b\frac{1}{2}(b+3)} \) by Lemma 3.1(d), becomes very small for large \( h \), where \( b = o(h) \).

Before we present an exact asymptotical evaluation of \( z_{h,b} \), we briefly discuss some aspects concerning the convergence of the sequence \( z_t \), \( t \geq 0 \). According to the proof of Theorem 3.1(a), (b), the polynomial \( P_{h,b}(z) \) has exactly one simple root \( z_{h,b} \) in the interval \([r_{b+1}, r_b]\). Hence, the equalities \( P_{h,b}(r_{b+1})P_{h,b}(r_b) < 0 \) and \( P'_{h,b}(z) \neq 0 \) hold in that interval. Indeed, we have \( P_{h,b}(r_{b+1}) = (1 - r_{b+1})n^{h-b\frac{1}{2}(b+3)} > 0 \) and \( P_{h,b}(r_b) = -n^{\frac{1}{2}b+1}(1 - r_{b+1}^{h-b-2}) < 0 \) by Lemma 3.1(d) and \( P'_{h,b}(z) < 0 \) by Lemma 3.2(a). Since additionally \( P_{h,b}(z) \) is convex in the interval \([r_{b+1}, r_b]\) by Lemma 3.2(b), the Newton-sequence \( z_0 = r_{b+1}, z_1, z_2, \ldots \) is strictly monotonically increasing and it converges quadratically to the root \( z_{h,b} \) in \([r_{b+1}, r_b]\), i.e. \( \limsup_{t \to \infty} \frac{|z_{t+1} - z_{h,b}|}{|z_t - z_{h,b}|^2} = \alpha > 0 \).

Now, let us turn to the asymptotical evaluation of \( z_{h,b} \). We compute successively \( z_0 := r_{b+1}, z_1, z_2, \ldots \). In each step we evaluate the approximant \( z_t \) around \( r_{b+1}^{h-b} \) and simplify the resulting expression by means of the explicit expressions presented in Lemma 3.1(d). Choosing this procedure, we obtain by a very lengthy computation, for \( b = o(h) \) and large \( h \):

\[
z_{h,b} = r_{b+1} + c_{b}^{(1)}r_{b+1}^{h-b-2} + c_{h,b}^{(2)}r_{b+1}^{2(h-b)-5} + c_{h,b}^{(3)}r_{b+1}^{3(h-b)-8}
+ O((h-b)^3r_{b+1}^{4(h-b)}),
\]

(18)
\[ c_b^{(1)} = -\frac{1}{p_{b+3}} r_{b+1}^2 p_b = \frac{1}{6(r+3)} (1 - \frac{r}{b+1})(4 \frac{r}{b+1} - 1); \]

\[ c_{h,b}^{(2)} = \frac{1}{[p_{b+3}]} r_{b+1}^4 p_{b+1} p_{b+3}^2 (h - b) + \frac{1}{2[p_{b+3}]} r_{b+1}^5 p_b \left[ 2 p_{b+1} p_{b+3} - p_b p_{b+3} \right] \]

\[ = \frac{1}{2(b+3)^2} (1 - \frac{r}{b+1})(4 \frac{r}{b+1} - 1) \left[ \xi_b^{(1)} (h - b) + \xi_b^{(0)} \right], \]

with \( \xi_b^{(0)} := (2 \frac{r}{b+1} + b - 2)(3 \frac{r}{b+1} - 1) \),

and \( \xi_b^{(1)} := 2(1 - \frac{r}{b+1})(4 \frac{r}{b+1} - 1); \)

\[ c_{h,b}^{(3)} = -\frac{3}{4[p_{b+3}]} r_{b+1}^6 p_{b+1}^3 (h - b)^2 \]

\[ + \frac{1}{4[p_{b+3}]} r_{b+1}^8 p_{b+1}^3 \left( p_b p_{b+3} - 6 \frac{r}{b+1} p_b p_{b+3} + 3 \frac{r}{b+1} p_b p_{b+3} \right) (h - b) \]

\[ + \frac{1}{6[p_{b+3}]} r_{b+1}^8 p_{b+1} \left( p_b^2 p_{b+3} p_{b+3} - 3 p_b p_{b+3}^2 \right) \]

\[ + 9 p_p^2 p_{b+3} p_{b+3}^2 - 6 \left[ p_b^2 \right]^2 \left[ p_{b+3}^2 \right]^2 \]

\[ = \frac{1}{6(b+3)^3} (1 - \frac{r}{b+1})(4 \frac{r}{b+1} - 1) \]

\[ \left[ \eta_b^{(2)} (h - b)^2 + \eta_b^{(1)} (h - b) + \eta_b^{(0)} \right], \]

with \( \eta_b^{(0)} := 120 \left( r_{b+1}^4 - 2(b^2 - 57 b + 155) r_{b+1}^3 \right. \]

\[ + 9 \left( 2 b^2 - 21 b + 30 \right) r_{b+1}^2 - 3(6b - 5)(6b - 5)(b - 5) \]

\[ + 2(b - 1)(b - 5), \]

and \( \eta_b^{(1)} := 3(1 - \frac{r}{b+1})(4 \frac{r}{b+1} - 1) \]

\[ \times \left[ 22 r_{b+1}^2 + (9 b - 29) r_{b+1} - 3 b + 7 \right], \]

and \( \eta_b^{(2)} := 9(1 - \frac{r}{b+1})^2(4 \frac{r}{b+1} - 1)^2. \)

In principle, the expansion for \( z_{h,b} \) could be carried out as far as we like but the higher terms become more and more complicated. Without going into detail, another approach to the computation of the asymptotic approximation given in (18) is the bootstrapping technique starting with \( z_0 := r_{b+1} \), and computing better estimates \( z_t, t = 1, 2, 3, \ldots \). In this way, we find the same approximation. Notice that \( r_2 = \frac{1}{2} \), and therefore \((c_1^{(1)}, c_{h,1}, c_{h,1}) = (\frac{1}{8}, \frac{1}{64} (h - 1), \frac{1}{1024} (h - 1)(3 h - 4)) \).

Thus,

\[ z_{h,1} = \frac{1}{2} + 2^{-h} + (h - 1) 2^{-2(h-1)} + (h - 1)(3 h - 4) 2^{-3(h-1)} \]

\[ ^1 \text{The abbreviations } p_b, p_{b+1}', p_{b+1}'' \text{ and } p_{b+1}''' \text{ stand for } p_b(r_{b+1}) \text{, } p_{b+1}'(r_{b+1}) \text{, } p_{b+1}''(r_{b+1}) \text{ and } p_{b+1}'''(r_{b+1}) \text{, respectively.} \]
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\[ + \mathcal{O}(h^3 2^{-4h}). \]

Table 2: The dominant singularities \( z_{h,b} \) for \( 3 \leq b \leq h, 3 \leq h \leq 11 \).

The upper (resp. lower) number appearing in an entry corresponds to the exact (resp. approximative) value of \( z_{h,b} \). The values are not rounded to the sixth decimal place. The exact and the approximate value coincide up to the sixth decimal place regarding the entries not marked with |.

\[
\begin{array}{cccccccccccc}
\hline
h \backslash b & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 \\
\hline
3 & 0.1 & 0.18 & 0.13 & 0.18 & 0.13 & 0.18 & 0.13 & 0.18 & 0.13 & 0.18 & 0.13 \\
4 & 0.57 & 0.53 & 0.53 & 0.53 & 0.53 & 0.53 & 0.53 & 0.53 & 0.53 & 0.53 & 0.53 \\
5 & 1.17 & 1.17 & 1.17 & 1.17 & 1.17 & 1.17 & 1.17 & 1.17 & 1.17 & 1.17 & 1.17 \\
6 & 1.77 & 1.77 & 1.77 & 1.77 & 1.77 & 1.77 & 1.77 & 1.77 & 1.77 & 1.77 & 1.77 \\
7 & 2.37 & 2.37 & 2.37 & 2.37 & 2.37 & 2.37 & 2.37 & 2.37 & 2.37 & 2.37 & 2.37 \\
8 & 2.97 & 2.97 & 2.97 & 2.97 & 2.97 & 2.97 & 2.97 & 2.97 & 2.97 & 2.97 & 2.97 \\
11 & 4.77 & 4.77 & 4.77 & 4.77 & 4.77 & 4.77 & 4.77 & 4.77 & 4.77 & 4.77 & 4.77 \\
\hline
\end{array}
\]
This approximation coincides with the terms up to \( j = 3 \) in the explicit expression for \( z_{h,1} \) established in (16). The exact and approximate values for \( z_{h,b}, 1 \leq b \leq h, 3 \leq h \leq 12 \), are presented in Table 2. Even for small \( h \), the derived approximation yields very good values for the dominant singularity \( z_{h,b} \).

**3.3 An asymptotic Equivalent to the Taylor Coefficients of \( G_{h,b}(z) \)**

In this subsection we shall determine the exact asymptotic behaviour of the coefficient at \( z^n \) in the expansion of the enumerator \( G_{h,b}(z) \) around \( z = 0 \).

**Theorem 3.2.** Let \( r_w := [4 \cos^2 \left( \frac{\pi}{w+2} \right)]^{-1}, w \in \mathbb{N} \), and \( p_k(z) \) be the Fibonacci polynomial defined in (4). Furthermore, let \( K_{h,h-1} = K_{h,h-2} := \frac{1}{h} \tan^2 \left( \frac{\pi}{h} \right), h \geq 3 \), and

\[
K_{h,b} := \frac{1 - z_{h,b}}{z_{h,b} \left[ p_{h+1}^2(z_{h,b}) - p_h(z_{h,b}) \right]} - (h - b),
\]

for \( 1 \leq b \leq h - 3 \), where \( z_{h,b} \) is the dominant pole of the enumerator \( G_{h,b}(z) \). An asymptotic equivalent to the coefficient \( \langle z^n; G_{h,b}(z) \rangle^2 \) is given by

\[
\langle z^n; G_{h,b}(z) \rangle = K_{h,b} z_{h,b}^{-n} + O(b^3 r_b^{-n}), \quad n \to \infty.
\]

**Proof:** First, let us consider the simple cases \( b \in \{ h - 1, h - 2 \} \).

It has been shown in the classical paper [1] that the \( n \)-th coefficient \( \phi_h(n) = \langle z^n; F_h(z) \rangle \) of the enumerator \( F_h(z) = z \frac{p_h(z)}{p_{h+1}(z)} \) introduced in (3) has the explicit representation

\[
\phi_h(n) = \frac{1}{h+1} \sum_{1 \leq j \leq \lfloor \frac{h}{2} \rfloor} \tan^2 \left( \frac{\pi j}{h+1} \right) [4 \cos^2 \left( \frac{\pi j}{h+1} \right)]^n, \quad n \geq 2.
\]

Splitting up the sum appearing on the right-hand side and using the inequalities \( \cos^2 \left( \frac{\pi j}{h+1} \right) \leq \cos^2 \left( \frac{\pi}{h+1} \right) \) and \( \tan^2 \left( \frac{\pi j}{h+1} \right) \leq \tan^2 \left( \frac{\pi}{h+1} \right) \lfloor \frac{h}{2} \rfloor \rfloor = \frac{2}{\pi} (5 + 3(-1)^h) \lfloor \frac{h}{2} \rfloor^2 + O(h), \quad 2 \leq j \leq \lfloor \frac{h}{2} \rfloor \), we further obtain for \( h \geq 4 \)

\[
\phi_h(n) = \frac{1}{h+1} \tan^2 \left( \frac{\pi}{h+1} \right) r_{h-1}^{-n} + O(h^2 [4 \cos^2 \left( \frac{2\pi}{h+1} \right)]^n), \quad n \geq 2. \quad (19)
\]
Clearly, this estimate holds for \( h \in \{2, 3\} \), too. Now, as it was observed at the end of Section 2, we have \( G_{h,h-2}(z) + z = G_{h,h-1}(z) = F_{h-1}(z) \) and therefore

\[
\langle z^n; G_{h,h-2}(z) \rangle = \langle z^n; G_{h,h-1}(z) \rangle = \langle z^n; F_{h-1}(z) \rangle = \phi_{h-1}(n)
\]

for \( n \geq 3 \). Combining this relation and the expression for \( \phi_h(n) \) given in (19), we immediately find the asymptotic equivalent stated in the theorem because \( z_{h,h-2} = z_{h,h-1} = \rho_h \) by Lemma 3.1(b) and \( 4 \cos^2 \left( \frac{2 \pi n}{h} \right) \leq r_h^{-1} < r_h^{-1}, \ h \geq 2 \).

Next, let us consider the cases \( 1 \leq b \leq h - 3 \). For \( b = 1 \), we have \( G_{h,1}(z) = \frac{(1-z)z^{-b+1}}{1-2z+2n^{-1}}, \ h \geq 2 \). This function is identical with the function \( D_{h-1}(z) \) already introduced in [5, formula (6)]. In Theorem 3(b) of that paper it has been proved that \( \langle z^n; D_h(z) \rangle = C_h q_h^{-n} + O(1) \), where \( C_h = \frac{(1-z_h)(2n^{-1})}{h^2(1-h)(1-q_h)} \) and \( q_h = z_{h+1,1} \). Hence, \( \langle z^n; G_{h,1}(z) \rangle = C_{h-1} z_{h+1,1}^{-n} + O(1) \). Since \( (p_1(z), p_4(z)) = (1, 1 - 2z) \), the expression for \( K_{h,1} \) given in the theorem is identical with \( C_{h-1} \) and our result is valid for \( b = 1 \).

Now, let \( 2 \leq b \leq h - 3 \). By Theorem 3.1(a), the enumerator \( G_{h,b}(z) \) has a dominant simple pole at \( z_{h,b} \). Hence, the partial fraction expansion of \( G_{h,b}(z) \) has the form

\[
G_{h,b}(z) = \overline{K}_{h,b} \left( 1 - \frac{z}{z_{h,b}} \right)^{-1} + R_{h,b}(z),
\]

where

\[
\overline{K}_{h,b} := \lim_{z \to z_{h,b}} \left( 1 - \frac{z}{z_{h,b}} \right) \frac{(1-z)z^{-b} p_h(z)}{p_{b+3}(z) + z^{-b} p_b(z)}
\]

and \( R_{h,b}(z) \) is a regular rational function for \( |z| \leq z_{h,b} \). Applying D’HOSPITAL’s rule and using the relation \( z_{h,b} = \frac{p_{b+3}(z_{h,b})}{p_b(z_{h,b})} \), we find \( \overline{K}_{h,b} = K_{h,b} \), where \( K_{h,b} \) is the quantity defined in the theorem. Thus, \( \langle z^n; G_{h,b}(z) \rangle = K_{h,b} z_{h,b}^{-n} + \langle z^n; R_{h,b}(z) \rangle \), where the coefficient \( \langle z^n; R_{h,b}(z) \rangle \) involves all the zeros of \( P_{h,b}(z) = p_{b+3}(z) + z^{-b} p_b(z) \), \( b \geq 2 \), with the exception of \( z_{h,b} \). Unfortunately, we have only insufficient information about these zeros at hand. It seems to be true that all roots of the polynomial \( P_{h,b}(z) \) are simple but the author is unable to prove this conjecture. However, there is a general theorem established in [13, Theorem 9.2] which can be successively applied in
order to determine the asymptotic growth of \( \langle z^n; R_{h,b}(z) \rangle \). For this purpose we consider the rational function \( \hat{G}_{h,b}(z) := z^{-2}G_{h,b}(z) = \frac{\hat{N}_{h,b}(z)}{P_{h,b}(z)} \), where \( \hat{N}_{h,b}(z) := (1-z)z^{h-b-2}p_b(z) \), and \( P_{h,b}(z) = p_{b+3}(z) + z^{h-b}p_b(z) \). Note that \( \langle z^n; \hat{G}_{h,b}(z) \rangle = \langle z^{n+2}; G_{h,b}(z) \rangle \), that the degree of the polynomial \( \hat{N}_{h,b}(z) \) is less than the degree of \( P_{h,b}(z) \) and that \( P_{h,b}(0) = p_{b+3}(0) \neq 0 \). Translating the result established in [13, Theorem 9.2] into our case (set \( k := 1 \) and \( \rho_1 := z_{h,b} \)), we obtain

\[
\left| \langle z^n; \hat{G}_{h,b}(z) \rangle \right| + \frac{\hat{N}_{h,b}(z)}{P_{h,b}(z)} | z_{h,b}^{n-1} \leq W R^{-n} + \delta^{-1} R^{-n} M, \]

where the following conditions have to hold:

(i) \( P_{h,b}(z) \) has only one simple root in \( |z| < R \);
(ii) \( R - z_{h,b} > \delta \) for some \( \delta > 0 \);
(iii) \( \max_{|z|=R} | \hat{G}_{h,b}(z) | \leq W \);
(iv) \( M = \left| \frac{\hat{N}_{h,b}(z)}{P_{h,b}(z)} \right| \).

Now, let \( R := r_b \) and \( \delta := r_b - \hat{r}_b \), with \( \hat{r}_b := [4 \cos \left( \frac{2\pi}{2b+3} \right) ]^{-1} \). The condition (i) is clearly satisfied by Theorem 3.1(a), (b). By Theorem 3.1(c) and (d), we have \( R - z_{h,b} = r_b - z_{h,b} > r_b - z_{b+3,b} > r_b - \hat{r}_b = \delta > 0 \), and the condition (ii) holds, too. Moreover, it is easily verified that \( \delta^{-1} \) is monotonically increasing with growing \( b \geq 2 \), and that \( \delta^{-1} \leq \frac{1}{2} \cos^2 \left( \frac{\pi}{2b+3} \right) \left( 2 \cos^2 \left( \frac{\pi}{2b+3} \right) - 1 \right)^{-1} b^3 = \mathcal{O}(b^3) \), for \( b \geq 2 \).

Next, the following computation shows that the upper bound \( W \) introduced in condition (iii) can be chosen as a constant, i.e. \( W = \mathcal{O}(1) \). Indeed, we have for \( |z| = r_b, 2 \leq b \leq h-3 \),

\[
| \hat{G}_{h,b}(z) | \leq \frac{|z|^{h-b-2} |1-z| |p_b(z)|}{|p_{b+3}(z)| + z^{h-b}p_b(z)} \leq \frac{|z|^{h-b-2}(1+|z|) |p_b(z)|}{|p_{b+3}(z)|} \leq \frac{r_b^{h-b-2}(1+r_b)}{r_b^{h-b}} \leq \frac{(\text{Lem.3.4})}{\min \leq 1 + r_b}{ \leq 1 + \frac{r_b}{\delta \leq u(b)}} = \mathcal{O}(1). \]
Note that the sequence \((u(b))_{b \geq 2}\) is positive and monotonically increasing with the limit \(10 (4 + 3\sqrt{2}) \approx 82.426406 \ldots\).

Finally, let us turn to the quantity \(M\) appearing in condition (iv). Since \(r_{b+1} < z_{h,b} < r_b\) by Theorem 3.1(b), \(p_2(z) = 1\), and \(p_b(z) < p_b(r_{b+1}) = (1 - r_{b+1}) r_{b+1}^{2(b-3)}\), \(b \geq 3\), by Lemma 3.1(d) and (e), we obtain, for \(2 \leq b \leq h - 3\),

\[
|\hat{N}_{h,b}(z_{h,b})| = |z_{h,b}|^{h-b-2} |1 - z_{h,b}| |p_b(z_{h,b})| \leq r_b^{h-b-2} (1 + r_b)(1 - r_{b+1}) r_{b+1}^{2(b-3)} \leq r_b (1 + r_b) r_{b+1}^{2(b-3)}.
\]

Hence, by Lemma 3.2(a)

\[
M \leq \frac{r_b (1 + r_b)(4 r_{b+1} - 1) r_{b+1}^{2(b-3)}}{(b-1) r_{b+1} r_b^{4b}} \leq \frac{r_b (1 + r_b)(4 r_{b+1} - 1)}{(b-1) r_{b+1}^{2}} = O(1),
\]

because \(r_{b+1} < r_b\). Note that the sequence \((v(b))_{b \geq 2}\) is positive and monotonically decreasing with \(v(b) \leq v(2) = \frac{3}{8}(5 + 3\sqrt{5}) = 4.390576 \ldots\).

Thus, we have verified the relation \(|\langle z^{n+2}; R_{h,b}(z)\rangle| = O(b^3 r_b^{-n})\), \(2 \leq b \leq h - 3\). This completes the proof because \(r_b^2 \in \left[1, \frac{1}{16}\right], b \geq 2\).

\(\square\)

**Remark 3.2.** (a) Using Lemma 3.1(d), (e) and Lemma 3.2(a), it is not hard to verify that the quantity \(K_{h,b}\) introduced in the preceding theorem is bounded, i.e. \(K_{h,b} = O(1), 1 \leq b < h, h \geq 3\).

(b) Evaluating the explicit expression for \(K_{h,b}\) stated in the previous theorem by means of (18) and using the explicit expressions presented in Lemma 3.1(d), we find the following approximation, for \(b = o(h)\) and large \(h\), by a lengthy computation:

\[
K_{h,b} = k_b^{(1)} r_{b+1}^{h-b-3} + k_b^{(2)} r_{b+1}^{2(h-b)-6} + k_b^{(3)} r_{b+1}^{3(h-b)-9} + O((h-b)^3 r_{b+1}^{4(h-b)}), \tag{20}
\]

where

\[
k_b^{(1)} = \frac{1}{b+3} (1 - r_{b+1})^2 (4 r_{b+1} - 1);
\]
The exact and approximate values for $K_{h,b}$, $1 \leq b < h$, $3 \leq h \leq 12$, are presented in Table 3. Even for small $h$, the derived approximation yields very good values for the quantity $K_{h,b}$.

\section{Enumeration and Distribution Results}

In this section we shall compute asymptotic equivalents to the number of all $b$-balanced ordered trees with $n$ nodes and of all such trees with height $h$. Furthermore, assuming that all $b$-balanced ordered trees with $n$ nodes are equally likely, we shall determine the exact asymptotic behaviour of the average height of such a tree together with the variance.

\begin{theorem}
\label{thm:average_height}
Let $r_w := [4 \cos^2 \left( \frac{\pi}{w+2} \right)]^{-1}$, $w \in \mathbb{N}$.

(a) The number $\ell_{h,b}(n)$ of all $b$-balanced ordered trees of height $h$ with $n$ nodes is given by $\ell_{1,0}(n) = \delta_{n,1}$, by $\ell_{2,0}(n) = 1 - \delta_{n,1}$, by $\ell_{h,b-1}(n) = 0$, $h \geq 2$, and for $0 \leq b \leq h - 2$, $h \geq 3$ by

$\ell_{h,b}(n) = K_{h+1,b+1} z_{h+1,b+1}^{n} + O((b+1)^3 r_{b+1}^{-n})$,

\end{theorem}
Table 3: The quantity $K_{h,b}$ for $3 \leq b < h$, $3 \leq h \leq 11$. The values of $K_{h,h-2}$ and $K_{h,h-1}$, $h \geq 3$, are explicitly given by $\frac{1}{h} \tan \left( \frac{1}{h} \right)$.

The upper (resp. lower) number appearing in the remaining entries corresponds to the exact (resp. approximative) value of $K_{h,b}$. The values are not rounded to the sixth decimal place. The exact and the approximate value coincide up to the sixth decimal place regarding the entries not marked with $|$. The values of $K_{h,b-1}$, $h \geq 3$, are explicitly given by $\frac{1}{h} \tan \left( \frac{1}{h} \right)$.

<table>
<thead>
<tr>
<th>$h \setminus b$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
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<tbody>
<tr>
<td>3</td>
<td>$K_{3,1}$</td>
<td>$K_{3,2}$</td>
<td></td>
<td></td>
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<tr>
<td>4</td>
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<td>1.48477</td>
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<tr>
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<td>0.004360</td>
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<tr>
<td>6</td>
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<td>0.006245</td>
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<tr>
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<td>0.000873</td>
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<tr>
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<td>0.000330</td>
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</table>
where $z_{h,b}$ (resp. $K_{h,b}$) is the dominant singularity of the numerator $G_{h,b}(z)$ (resp. the quantity) introduced in Theorem 3.1 (resp. in Theorem 3.2) with the asymptotic expansion established in (18) (resp. (20)).

(b) The number $t_b(n)$ of all $b$-balanced ordered trees with $n$ nodes is for fixed $b \in \mathbb{N}_0$ and all $\delta > 0$ given by

$$
t_b(n) = \frac{1-r_{b+2}}{\ln(r_{b+2})} n^{-1} r_{b+2}^{-n} \left[ 1 + \eta_{h,b}(n) \right] + O\left(\frac{\ln(n)}{n^2} r_{b+2}^{-n}\right),
$$

where $\eta_{h,b}(n)$, $s \geq 0$, is the oscillating function

$$
\eta_{h,b}(n) = 2 \sum_{k \geq 1} 3^k \left( \Gamma^{(s)}(1 - 2\pi ik \ln(r_{b+2})) e^{2\pi ik \ln\left(\frac{(1-r_{b+2})/(4r_{b+2}^{-1})}{\ln(r_{b+2})}\right)} \right)
$$

with $\eta_{h,b}(n) = \eta_{h,b}(r_{b+2} n)$ and $|\eta_{h,b}(n)| < 8.646828 \ldots \times 10^{-3}$. Here, $i^2 = -1$ and $\Gamma^{(s)}$ denotes the $s$-th derivative of the complete gamma function.

**Proof:** (a) Inserting the explicit expression for $G_{h,b}(z)$ presented in (6) into (8), we obtain $L_{1,0}(z) = z$, $L_{2,0}(z) = \frac{z^2}{1-z}$ and $L_{h,h-1}(z) = 0$, $h \geq 2$. This proves the result for $\ell_{h,b}(n) = (z^n; L_{h,b}(z))$, $(h,b) \in \{(1,0),(2,0),(h,h-1), h \geq 2$. With respect to the general case $\ell_{h,b}(n)$, $0 \leq b \leq h -2$, $h \geq 3$, formula (8) and Theorem 3.2 tell us

$$
\ell_{h,0}(n) = K_{h+1,1} z_{h+1,1}^{-n} + O(r_1^{-n}), \ h \geq 3,
$$

and additionally for $b \geq 1$ by means of Theorem 3.1(b) and Remark 3.2(a)

$$
\ell_{h,b}(n) = [K_{h+1,b+1} z_{h+1,b+1}^{-n} + O((b+1)^3 r_{b+1}^{-n})]
- [K_{h+1,b} z_{h+1,b}^{-n} + O(b^3 r_b^{-n})]
+ [K_{h,b-1} z_{h,b-1}^{-n} + O((b-1)^3 r_{b-1}^{-n})]
= K_{h+1,b+1} z_{h+1,b+1}^{-n} + O((b+1)^3 r_{b+1}^{-n}), \ 1 \leq b \leq h - 2, \ h \geq 3.
$$

(b) We obtain by the first three alternatives for $\ell_{h,b}(n)$ given in part (a)

$$
t_b(n) = \sum_{b< h \leq n} \ell_{h,b}(n) = \delta_{b,0} + \sum_{\max\{3,b+2\}\leq h \leq n} \ell_{h,b}(n), \hspace{1cm} (21)
$$
and further by the fourth alternative and by \((K_{3,1}, z_{3,1}) = (1, 1)\) (cf. Theorem 3.2 and Remark 3.1(a))

\[
r_{b+2}^* t_b(n) = S_b(n) + O(n (b + 1)^3 r_{b+1}^* r_{b+2}^*), \quad b \geq 0,
\]

where

\[
S_b(n) := \sum_{b+2 \leq h \leq n} K_{h+1,b+1} (r_{b+2}^* z_{h+1,b+1})^{-n}.
\]

In order to compute an asymptotic equivalent to the sum appearing on the right-hand side, we first approximate the quantity

\[
(r_{b+2}^* z_{h+1,b+1})^{-n}.
\]

Using the asymptotic expansion established in (18) and the expansions of \(\ln(1+x)\) and \(e^x\), the standard “exp/log”-technique ([11, pp. 174-175 and p. 190]) yields, for all fixed \(\epsilon > 0\),

\[
(r_{b+2}^* z_{h+1,b+1})^{-n} = \begin{cases} 
\zeta_{h,b}(n) e^{-c(1)_{b+1} n (r_{b+2}^* z_{h+1,b+1})^{-3}}, & \text{if } h \geq b + 3 + N_{\epsilon,b}(n); \\
O(\epsilon^{-n^*}), & \text{if } h < b + 3 + N_{\epsilon,b}(n),
\end{cases}
\]

where

\[
N_{\epsilon,b}(n) := \frac{\ln(c(1)_{b+1})}{\ln(r_{b+2}^*)} = (1 - \epsilon) \log_4(n) - 3 \log_4(b) + O(1), \quad n \to \infty,
\]

and

\[
\zeta_{h,b}(n) = 1 + \kappa_{h,b}^{(1)} \frac{2(h-b-3)}{r_{b+2}^*} n + \kappa_{h,b}^{(2)} \frac{3(h-b-3)}{r_{b+2}^*} n + \kappa_{h,b}^{(3)} \frac{4(h-b-3)}{r_{b+2}^*} n^2 + O\left(\frac{\ln(n)^3}{n^{3-\epsilon}}\right),
\]

with

\[
\kappa_{h,b}^{(1)} := \frac{1}{2} \left( c_{b+1}^{(1)} \right)^2 - 2 c_{h+1,b+1}^{(2)} = -\frac{\zeta_b^{(0)}}{4(b+3)^2} \left( c_b^{(0)} (h - b) + \zeta_b^{(1)} \right),
\]

\[
\kappa_{h,b}^{(2)} := -\frac{1}{3} \left( c_{b+1}^{(1)} \right)^3 - 3 c_{b+1}^{(1)} c_{h+1,b+1}^{(2)} + 3 c_{h+1,b+1}^{(3)}
\]

\[
= -\frac{\zeta_b^{(0)}}{48(b+4)^2} \left[ 9 \left( c_b^{(0)} \right)^2 (h - b)^2 + 18 c_b^{(0)} c_b^{(1)} (h - b) + 4 c_b^{(2)} \right],
\]

\[
\kappa_{h,b}^{(3)} := \frac{1}{8} \left( c_{b+1}^{(1)} \right)^2 - 2 c_{h+1,b+1}^{(2)} = \frac{1}{2} \left( \kappa_{h,b}^{(1)} \right)^2.
\]
Here, $c_b^{(1)}$, $c_{h,b}^{(2)}$ and $c_{h,b}^{(3)}$ are the quantities defined in Remark 3.1(b) and

\[
\begin{align*}
\zeta_b^{(0)} &= 2(1 - r_{b+2})(4 r_{b+2} - 1), \\
\zeta_b^{(1)} &= 10 r_{b+2}^2 + (3 b - 10) r_{b+2} - b + 2, \\
\zeta_b^{(2)} &= 224 r_{b+2}^4 - 2 (b^2 - 73 b + 214) r_{b+2}^3 + 6 (3 b^2 - 35 b + 45) r_{b+2}^2 \\
&\quad - (12 b^2 - 87 b + 65) r_{b+2} + (2 b - 1)(b - 5).
\end{align*}
\]

Now, taking the approximation (23) with $\zeta(h,b,n) = 1 + O\left(\frac{\ln(n)}{n^{1/2}}\right)$, we find by means of the asymptotic expansion for $K_{h,b}$ stated in (20) that

\[
S_b(n) = S_{h,b}^{(1)}(n) + S_{h,b}^{(2)}(n) - \zeta_{h,b}(n),
\]

where

\[
\begin{align*}
S_{h,b}^{(1)}(n) &= \sum_{r_{b+2} \leq h < b+3 + N_{b,\epsilon}} K_{h+1,b+1} \left( r_{b+2}^{-1} z_{h+1,b+1} \right)^{-n} \\
&= O(\epsilon^{-n}) \sum_{r_{b+2} \leq h < b+3 + N_{b,\epsilon}} \left[ k_{b+1}^{(1)} r_{b+2}^{h-b-3} + O((h-b) r_{b+2}^{2(h-b)}) \right] \\
&= O(\epsilon^{-n}),
\end{align*}
\]

and

\[
\begin{align*}
S_{h,b}^{(2)}(n) &= \sum_{h \geq b+3 + N_{b,\epsilon}} K_{h+1,b+1} \left( r_{b+2}^{-1} z_{h+1,b+1} \right)^{-n} \\
&= \left[ 1 + O\left(\frac{\ln(n)}{n^{1/2}}\right) \right] \sum_{h \geq b+3 + N_{b,\epsilon}} \left[ k_{b+1}^{(1)} r_{b+2}^{h-b-3} + O((h-b) r_{b+2}^{2(h-b)}) \right] \\
&\quad \times e^{-c_{b+1}^{(1)} n r_{b+2}^{h-b-3}} \\
&= \left[ k_{b+1}^{(1)} \sum_{h \geq b+3 + N_{b,\epsilon}} r_{b+2}^{h-b-3} e^{-c_{b+1}^{(1)} n r_{b+2}^{h-b-3}} \right] + O\left(\frac{\ln(n)}{n^{1/2}}\right) \\
&= k_{b+1}^{(1)} \left[ \sum_{h \geq 1} r_{b+2}^{h-b-3} e^{-c_{b+1}^{(1)} n r_{b+2}^{h-b-3}} \right] - \sum_{1 \leq h < b+3 + N_{b,\epsilon}} r_{b+2}^{h-b-3} e^{-c_{b+1}^{(1)} n r_{b+2}^{h-b-3}} + O\left(\frac{\ln(n)}{n^{1/2}}\right) \\
&= O(e^{-n}).
\end{align*}
\]
\[ k_{b+1}^{(1)} \sum_{h \geq 1} r_{b+2}^{h-b-3} e^{-c_{b+1}^{(1)} n r_{b+2}^{h-b-3}} + \mathcal{O}(\frac{\ln(n)}{n^{2-2\epsilon}}), \]

and

\[ S_{b,b}^{(3)}(n) = \sum_{h>n} K_{h+1,b+1} (r_{b+2}^{h-1} 2^{h+1,b+1})^{-n} \]

\[ = [1 + \mathcal{O}(\frac{\ln(n)}{n^{2-2\epsilon}})] \sum_{h>n} [k_{b+1}^{(1)} r_{b+2}^{h-b-3} + \mathcal{O}((h-b) r_{b+2}^{2(h-b)})] \times \frac{e^{-c_{b+1}^{(1)} n r_{b+2}^{h-b-3}}}{\leq 1} \]

\[ = \mathcal{O}(r_{b+2}^{-n}). \]

Thus, introducing the series

\[ U_{s,q,y}(n) := \sum_{h \geq 1} h^s y^h e^{-n q y^h}, \quad s \geq 0, \quad q > 0, \quad y < 1, \quad s,q,y \text{ fixed} \quad (24) \]

we have shown

\[ S_b(n) = k_{b+1}^{(1)} r_{b+2}^{b-3} U_{0,c_{b+1}^{(1)} r_{b+2}^{b-3},r_{b+2}^{b+3}}(n) + \Omega, \]

where \( \Omega := \mathcal{O}(e^{-n}) + \mathcal{O}(\frac{\ln(n)}{n^{2-2\epsilon}}) + \mathcal{O}(r_{b+2}^{-n}) = \mathcal{O}(\frac{\ln(n)}{n^{2-2\epsilon}}) \). Therefore by (22)

\[ r_{b+2}^{n} l_b(n) = k_{b+1}^{(1)} r_{b+2}^{b-3} U_{0,c_{b+1}^{(1)} r_{b+2}^{b-3},r_{b+2}^{b+3}}(n) + \mathcal{O}(\frac{\ln(n)}{n^{2-2\epsilon}}) + \mathcal{O}(n(b+1)^3 [r_{b+1}^{b+2} r_{b+2}^{-1}]^n). \quad (25) \]

It remains to derive an asymptotic equivalent to the series \( U_{s,q,y}(n) \) established in (24). This can be done by the MELLIN-transform technique (cf. e.g. [3]) yielding a complex integral which can be computed by an application of the residue theorem. In this way, an asymptotic equivalent to a function very similar to \( U_{s,q,y}(n) \) has already been computed in [5, Lemma 2]. Almost the same computation carried out there yields in the present case

\[ U_{s,q,y}(n) = -\left[ -\frac{\ln(n q)^s}{q \ln(y)^{s+2}} \frac{\ln(n)}{n} \left[ (1) + \theta_{0,q,y}(n) \right] \right] \]
\[ - s \left[ - \ln(n q) \right]_{q \ln(n)}^{s-1} n^{-1} \left[ \Gamma'(1) + \theta_{1,q,y}(n) \right] \\
- \left( \frac{s}{2} \right) \left[ - \ln(n q) \right]_{q \ln(n)}^{s-2} n^{-1} \left[ \Gamma''(1) + \theta_{2,q,y}(n) \right] \\
+ O\left( \frac{\ln(n)^{s-3}}{n} \right), \tag{26} \]

where \( \theta_{m,q,y} \) is the oscillating function

\[
\theta_{m,q,y}(n) := 2 \sum_{k \geq 1} \Re \left( \Gamma^{(m)}(1 - \frac{2\pi ik}{\ln(y)}) e^{2\pi ik \ln(n q) / \ln(y)} \right), \quad m \geq 0,
\]

with \( \theta_{m,q,y}(n) = \theta_{m,q,y}(yn) \). Note that \( \theta_{s,c}^{(1)} b + 1 r_{b+2} - b - 3 b + 2 r_{b+2} \) is identical with the function \( \eta_{s,b} \) defined in the theorem. Now, inserting the asymptotic expansion given in (26) with \( (m,q,y) := (0,c^{(1)} b + 1 r_{b+2} - b - 3 b + 2 r_{b+2}) \) into (25), we obtain the asymptotic result stated in part (b) of our theorem by means of the explicit expressions for \( c^{(1)} b \) and \( k^{(1)} b \) presented in (18) and Remark 3.2(b), respectively.

Finally, since the identity \( |\Gamma(1 + it)|^2 = \frac{\pi t}{\sinh(\pi t)} \) is valid, we find the upper bound

\[
|\eta_{0,b}(n)| \leq 2 \sum_{k \geq 1} |\Gamma(1 - \frac{2\pi ik}{\ln(r_{b+2})})| \\
= \eta_{0,b} := 2 \sum_{k \geq 1} \left[ \frac{2\pi k^2}{\ln(r_{b+2}) \sinh(\frac{2\pi k^2}{\ln(r_{b+2})})} \right]^{\frac{1}{2}} \\
\leq \eta_{0,\frac{1}{4}} = 8.646 \ldots \times 10^{-3}.
\]

The estimate \( (*) \) is valid because \( r_{b+2} > \frac{1}{4} \) and \( \frac{x}{\sinh(x)} \) is a strictly monotonically increasing function for \( x < 0 \).

**Remark 4.1.** (a) The first few numerical values of the upper bound \( \eta_{0,b} \) for \( |\eta_{0,b}(n)| \) introduced at the end of the proof of the preceding theorem are summarized in Table 4.

(b) By the previous theorem we have, for fixed \( b \) and large \( n \),

\[
t_b(n) \sim \alpha_b \xi_b^b n^{-1} \left[ 1 + \eta_{0,b} \right], \quad |\eta_{0,b}(n)| < \eta_{0,b}, \quad \eta_{0,b}(n) = \eta_{0,b}(r_{b+2} n),
\]

with \( \alpha_0 = \frac{1}{2 \ln(2)} \geq \alpha_b = -\frac{1 - r_{b+2}}{\ln(r_{b+2})} = \frac{3}{8 \ln(2)} + \frac{\pi^2 (3 - 2 \ln(2))}{16 \ln(2)^2} b^2 - O(b^{-3}) \),

\( b \to \infty \), and \( \xi_0 = 2 \leq \xi_b = r_{b+2}^{-1} = 4 - 4 \pi^2 b^2 + O(b^{-3}) \), \( b \to \infty \).
particular, we find for $b \in \{0, 1, 2, 3, 4\}$ and for large $n$:

$$t_0(n) \sim \frac{1}{\ln(2)n} 2^{n-1} [1 + \eta_{0,0}(n)], \quad |\eta_{0,0}(n)| < \eta_{0,0}, \quad \eta_{0,0}(n) = \eta_{0,0}(\frac{1}{2} n);$$

$$t_1(n) \sim \frac{\phi 2n^{-1} [1 + \eta_{0,1}(n)], \quad |\eta_{0,1}(n)| < \eta_{0,1}, \quad \eta_{0,1}(n) = \eta_{0,1}(\phi^{-2} n); \quad \text{where } \phi \text{ is the 'golden ratio'};$$

$$t_2(n) \sim \frac{2}{\ln(3)n} 3^{n-1} [1 + \eta_{0,2}(n)], \quad |\eta_{0,2}(n)| < \eta_{0,2}, \quad \eta_{0,2}(n) = \eta_{0,2}(\frac{1}{3} n);$$

$$t_3(n) \sim \frac{e^{-1}}{\ln(3)n} c^{n-1} [1 + \eta_{0,3}(n)], \quad |\eta_{0,3}(n)| < \eta_{0,3}, \quad \eta_{0,3}(n) = \eta_{0,3}(c^{-1} n) \text{ with } c := 4 \cos(\frac{\pi}{7});$$

$$t_4(n) \sim \frac{e^{-1}}{\ln(3)n} c^{n-1} [1 + \eta_{0,4}(n)], \quad |\eta_{0,4}(n)| < \eta_{0,4}, \quad \eta_{0,4}(n) = \eta_{0,4}(c^{-1} n) \text{ with } c := 2 + \sqrt{2}. $$

Note that the result with respect to $t_0(n)$ has already been proved in [5]. The first few exact and asymptotic values for $t_b(n)$ are summarized in Table 5.

(c) The oscillating functions $\eta_{s,b}(n)$ introduced in the previous theorem are bounded for fixed $s \geq 1$, too. We obtain $|\eta_{s,b}(n)| < \eta_{s,b} := 2 \sum_{k \geq 1} |\Gamma(s)(1 - \frac{2\pi ik}{\ln(n+2)})|$. The first few numerical values of the upper bound $\eta_{s,b}$, $s \in \{1, 2\}$, are presented in Table 6.

Assuming that all $b$-balanced ordered trees with $n$ nodes are equally likely, the quotient $\omega_{b,h}(n) \coloneqq \frac{t_{b,h}(n)}{t_b(n)}$, is the probability that such a tree has the height $h$. The $s$-th moment about the origin $\mathbb{E}[H_b^s(n)]$ of the random variable $H_b(n)$ taking the value $h$ with the probability

<table>
<thead>
<tr>
<th>$b$</th>
<th>0</th>
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<th>2</th>
<th>3</th>
<th>4</th>
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<tr>
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<td>$8.507 \times 10^{-3}$</td>
<td>$8.538 \times 10^{-3}$</td>
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Table 4: The numerical values of the upper bound $\eta_{0,b}$. The values are not rounded to the sixth decimal place.
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<td>9999</td>
<td>10000.000</td>
<td>10000.000</td>
<td>10000.000</td>
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</tbody>
</table>

Table 5: The exact [ex.] and asymptotical [as.] values of the number $t_b(n)$ of $b$-balanced ordered trees with $n$ nodes. The values are not rounded to the fourth decimal place.
The values are not rounded to the sixth decimal place.

Using the definition of $\omega_{b,0}$ we find by a similar lengthy computation as in the proof of Theorem 4.1(b) the result stated in (23), together with the asymptotic expansion for $K_{b,n}$ presented in (20), we find by a similar lengthy computation as in the proof of Theorem 4.1(b)

$$r_{b+2}^n \sum_{b < h \leq n} h^s \ell_{h,b}(n) = r_{b+2}^n \left[ \delta_{b,0} \left( \delta_{n,1} + 2^s [1 - \delta_{n,1}] \right) \right]$$

$$+ \sum_{\max\{3,b+2\} \leq h \leq n} h^s \ell_{h,b}(n)$$

Table 6: The numerical values of the upper bound $\eta_{s,b}$, $s \in \{1, 2\}$. The values are not rounded to the sixth decimal place.


<table>
<thead>
<tr>
<th>$b$</th>
<th>0</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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</thead>
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<td>$\eta_{1,b}$</td>
<td>2.645 078</td>
<td>1.081 682</td>
<td>3.446 692</td>
<td>5.938 005</td>
<td>8.070 653</td>
<td>9.785 936</td>
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<td>$10^{-5}$</td>
<td>$10^{-3}$</td>
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<td>$\eta_{2,b}$</td>
<td>6.978 935</td>
<td>2.530 602</td>
<td>7.643 819</td>
<td>1.278 774</td>
<td>1.706 847</td>
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<td></td>
<td>$10^{-5}$</td>
<td>$10^{-3}$</td>
<td>$10^{-3}$</td>
<td>$10^{-2}$</td>
<td>$10^{-2}$</td>
<td>$10^{-2}$</td>
</tr>
</tbody>
</table>

Here, $\eta_{s,b}(n)$ is the oscillating function introduced in Theorem 4.1(b).
\[ h^s K_{b+1,b+1} \left( r_{b+2}^{-1} s_{b+1,b+1} \right)^n \]
\[ + O(n^{s+1} (b+1)^3 r_{b+1}^{-n} r_{b+2}^{-1}) \]
\[ = k_{b+1}^{(1)} r_{b+2}^{-b-3} U_{s_{b+1,b+2}} \left( -b-3, r_{b+2}^{-1} \right) (n) + O\left( \frac{\ln(n)^{s+1}}{n^{b+2}} \right). \]

Hence, by (27)
\[ \mathbb{E}[H_b(n)] = \frac{1}{t_b(n)} k_{b+1}^{(1)} r_{b+2}^{-n-b-3} U_{s_{b+1,b+2}} \left( -b-3, r_{b+2}^{-1} \right) (n) + O\left( \frac{\ln(n)^{s+1}}{t_b(n)^{n^{b+2}}} \right). \]

Using Theorem 4.1(b) and the asymptotic expression for \( U_{s,q,r}(n) \) given in (26), a straightforward computation yields the stated result.

Following the classical paper [1], the average height of an ordered tree with \( n \) nodes is asymptotically given by \( \sim \sqrt{\pi n - \frac{3}{2}}, \ n \to \infty \), provided that all \( n \)-node ordered trees are equally likely; the variance is asymptotically given by \( \sim \frac{1}{3} \pi (\pi - 3) n + \frac{1}{12} \pi (\pi + 1), \ n \to \infty \) (see [4]).

The following theorem presents analogous asymptotic equivalents to the average height \( h_b(n) := \mathbb{E}[H_b(n)] \) of a \( b \)-balanced ordered tree with \( n \) nodes and to the variance \( \sigma_b(n)^2 := \mathbb{E}[H_b^2(n)] - (\mathbb{E}[H_b(n)])^2 \).

**Theorem 4.2.** Assume that all \( b \)-balanced ordered trees with \( n \) nodes are equally likely. The average height \( h_b(n) \) of such a tree is asymptotically given by
\[ h_b(n) \sim -\frac{1}{\ln(r_{b+2})} \ln(n) + \beta_b + \chi_b(n), \ b \text{ fixed}, \ n \to \infty. \]

Here, \( \beta_b \) denotes the quantity \( \beta_b := -\frac{1}{\ln(r_{b+2})} \ln(e^\gamma (1 - r_{b+2}^{-1} (4r_{b+2}^{-1} - 1))), \)
where \( \gamma \) is EULER’s constant, and \( \chi_b(n) \) is a bounded oscillating function with \( \chi_b(n) = \chi_b(r_{b+2}^{-1} n) \) and \( |\chi_b(n)| < C_1 := 3.375453 \ldots \times 10^{-2}. \)

The variance is asymptotically given by \( \sigma_b^2(n) \sim \frac{n^2}{6 (\ln(r_{b+2}))^2} + \varphi_b(n), \) where \( \varphi_b(n) \) is a bounded oscillating function with \( \varphi_b(n) = \varphi_b(r_{b+2}^{-1} n) \) and \( |\varphi_b(n)| < C_2 := 1.595432 \ldots \times 10^{-1}. \)

**Proof:** Since \( \Gamma'(1) = -\gamma \), the preceding lemma, with \( s = 1 \), tells us that
\[ h_b(n) \sim -\frac{1}{\ln(r_{b+2})} \beta_b(n) + \frac{1}{\ln(r_{b+2})} \frac{\eta_b(n) - \gamma}{\theta_b(n) + 1}. \]
Rearranging the terms appearing on the right-hand side, we find the asymptotic equivalent to $h_b(n)$ stated in the theorem, where

$$\chi_b(n) := \frac{1}{\ln(r_{b+2})} \frac{\eta_{1,b}(n) + \gamma \eta_{0,b}(n)}{1 + \eta_{0,b}(n)}.$$ 

Since $\eta_{b,n}(n) = \eta_{b,n}(r_{b+2} n)$, we also have $\chi_b(n) = \chi_b(r_{b+2} n)$. Moreover, we find by Remark 4.1(a), (c)

$$|\chi_b(n)| \leq \chi_b := \frac{1}{|\ln(r_{b+2})(1-\eta_{0,b}(n))|} \left( |\eta_{1,b}(n)| + \gamma |\eta_{0,b}(n)| \right)
< \frac{1}{|\ln(r_{b+2})(1-\eta_{0,b})|} \left( \eta_{1,b} + \gamma \eta_{0,b} \right)
< \frac{1}{\ln(2) (1-\eta_{0,\infty})} \left( \eta_{1,\infty} + \gamma \eta_{0,\infty} \right) = C_1.$$ 

With respect to the variance, the preceding Lemma 4.1 with $s \in \{1,2\}$ yields

$$\sigma_b^2(n) \sim \frac{1}{\ln(r_{b+2})^2} \left[ 1 + \eta_{0,b}(n) \right] \left( \Gamma(1+\eta_{0,b}(n)) - \left( \Gamma(1+\eta_{1,b}(n)) \right)^2 \right)$$

$$= \frac{\pi^2}{6 (\ln(r_{b+2})^2 + \varphi_b(n)},$$

where $\varphi_b(n) := \frac{\left[ \eta_{1,b}(n) - \frac{\eta_{0,b}(n)}{2} \right] \left[ 1+\eta_{0,b}(n) \right] + \gamma^2 \eta_{0,b}(n) + \eta_{1,b}(n) \left[ 1 - \eta_{1,b}(n) \right]}{\ln(r_{b+2})^2} \left[ \frac{\eta_{0,b}(n)}{2} \right].$

Here, we have used the equality $\Gamma'(1) = \gamma^2 + \frac{\pi^2}{6}$. Again, the relation $\varphi_b(n) = \varphi_b(r_{b+2} n)$ is fulfilled and we obtain by Remark 4.1(a), (c)

$$|\varphi_b(n)| \leq \varphi_b := \frac{1}{\ln(r_{b+2})^2} \left[ \frac{1}{1-\eta_{0,b}(n)} \right]^2$$

$$\times \left( |\eta_{2,b}(n)| + \frac{\pi^2}{6} |\eta_{0,b}(n)| \right) \left( 1 + |\eta_{0,b}(n)| \right)$$

$$+ \gamma^2 |\eta_{0,b}(n)| + |\eta_{1,b}(n)| \left( 2 \gamma + |\eta_{1,b}(n)| \right)$$

$$< \frac{1}{\ln(2) \left[ 1-\eta_{0,\infty} \right]^2} \left[ \left( \eta_{2,\infty} + \frac{\pi^2}{6} \eta_{0,\infty} \right) (1 + \eta_{0,\infty}) \right.$$ 

$$+ \gamma^2 \eta_{0,\infty} + \eta_{1,\infty} \left( 2 \gamma + \eta_{1,\infty} \right) \right) = C_2.$$ 

This completes the proof. 

\[ \square \]

**Remark 4.2.** (a) The first few numerical values of the quantity $\beta_b$ appearing in the preceding theorem are summarized in Table 7. It is easily verified that $\beta_b = \frac{3}{\ln(4)} \ln(b) + O\left( \frac{\ln^{(4)} b}{\ln(b)} \right),$ $b \to \infty.$
The first few numerical values for the upper bound $\chi_b$ (resp. $\varphi_b$) of the amplitude $|\chi_b(n)|$ (resp. $|\varphi_b(n)|$) of the oscillating functions appearing in the proof of the previous theorem are given in Table 8. The first few exact and asymptotic values of the average height $h_b(n)$ and of the variance $\sigma_b^2(n)$ are summarized in Table 9.

### 5 Concluding Remarks

In this paper we have presented a detailed average case analysis of $b$-balanced ordered $n$-node trees for fixed $b \geq 0$ and large $n$. However, the computations and results presented raise some questions:

- What is the average behaviour of $b$-balanced trees when $b$ is not assumed to be fixed?
- For the expected height of $b$-balanced ordered trees with $n \geq$
Table 9: The exact [ex.] and asymptotical [as.] values of the average height \( h_b(n) \) and of the variance \( \sigma^2_b(n) \). In each entry the upper number and lower number (in italics) indicate \( h_b(n) \) and \( \sigma^2_b(n) \), respectively. The upper bounds \( \Phi_b \) of the amplitudes \( |\phi_b(n)| \) are given in Table 8. The values are not rounded to the fourth decimal place.
3 nodes the parameter \( b \in \mathbb{N}_0 \) controls the transition from all totally balanced \( n \)-node trees \((b = 0)\) to all ordered trees with \( n \) nodes \((b \leq n - 3)\). In the course of this transition, the expected height changes from \( \Theta(\log(n)) \) (see \([5]\)) to \( \Theta(\sqrt{n}) \) (see \([1]\)). How could we characterize this transition with respect to \( b \) as a function in \( n \)?

- Another interesting problem is the computation of the average value \( b(n) \) such that an ordered tree with \( n \) nodes is \( b(n) \)-balanced assuming a uniform distribution of all ordered \( n \)-node trees. [It is easy to show that for uniformly distributed ordered trees with \( n \) nodes and fixed height \( h \) a random tree is asymptotically \( b_h \)-balanced with \( b_h \sim h - 2 \), \( n \to \infty \); the variance is asymptotically \( o(1), n \to \infty \).]

- The distribution of the heights in ordered trees obeys a limiting theta distribution (see \([2], [4]\)). What is the limit law for the height of \( b \)-balanced ordered trees?

- It remains an open problem whether the polynomials \( P_{h,k}(z) \) introduced in Lemma 3.2 only have simple roots. There is numerical evidence that this is indeed the case but so far the author was not able to prove this conjecture.

- The considerations presented in this paper can be extended to other classes of ordered trees, at least in a formal sense. Following \([10]\), the generating function \( Y(z) := \sum_{n \geq 1} t(n) z^n \) of the number \( t(n) \) of all trees with \( n \) nodes appearing in a simply generated family of trees satisfies the functional equation \( Y(z) := z \phi(Y(z)) \), where \( \phi(y) := \sum_{\lambda \geq 0} c_\lambda y^\lambda \) with \( c_0 = 1 \), \( c_\lambda \in \mathbb{N}_0 \) for \( \lambda \in \mathbb{N} \), and \( c_\lambda \in \mathbb{N} \) for some \( \lambda \in \mathbb{N} \{1\} \). This definition includes all families of unlabelled trees defined by restrictions on the set of the allowed node degrees such as \( t \)-ary trees \((\phi(y) := 1 + y^t, t \in \mathbb{N} \{1\})\), \( extended binary trees \((\phi(y) := 1 + y^2)\), \( binary trees \((\phi(y) := (1 + y)^2)\), \( unary-binary trees \((\phi(y) := 1 + y + y^2)\), \( unbalanced 2-3-trees \((\phi(y) := 1 + y^2 + y^3)\) or \( ordered trees \((\phi(y) := (1 - y)^{-1})\) considered in this paper.]
It is not hard to see that the generating function $A_h(z,y)$ of the number of all 0-balanced simply generated trees with $n$ nodes, $m$ leaves and height $h$ (cf. formula (1)) is recursively given by $A_{h+1}(z,y) = z\left(\phi(A_h(z,y)) - 1\right)$ with the initial condition $A_1(z,y) = zy$. Since the generating function $F_k(z)$ of the number of all simply generated trees with $n$ nodes and height less than or equal to $k$ (cf. formula (3)) satisfies the recurrence (see [2]) $F_{k+1}(z) = z\phi(F_k(z))$ with the initial condition $F_0(z) = 0$, the generating functions $T_{h,b}(z)$, $G_{h,b}(z)$ and therefore $L_{h,b}(z)$ introduced in the formulae (2), (6) and (8) are defined in a recursive way for $b$-balanced simply generated trees.

For ordered trees, the recurrences for $A_h(z,y)$ and $F_k(z)$ have the explicit solutions presented in (1) and (3), respectively; for $t$-ary trees, the recurrence for $A_h(z,y)$ has the solution $A_h(z,y) = z^t^{n-1}y^{t^{h-1}}$, but there does not exist an explicit expression for $F_k(z)$. Generally, explicit solutions for $A_h(z,y)$ and $F_k(z)$ are not available and we only have recursive formulae. Thus, in order to obtain enumeration and distribution results in the case of $b$-balanced simply generated trees, more powerful and refined methods must be developed.

Acknowledgements

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References


