

A note on plane trees with decreasing labels

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ABSTRACT

This note derives asymptotic upper and lower bounds for the number of planted plane trees on n nodes assigned labels from the set $\{1, 2, \dots, k\}$ with the restriction that on any path from the root to a leaf, the labels must strictly decrease. We illustrate an application to calculating the largest eigenvalue of the adjacency matrix of a tree.

Keywords: planted plane trees, decreasing labels, eigenvalues of trees

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1. Introduction

In this note, we count the number of planted plane trees (also sometimes called ordered trees) on n nodes, each node is given a label from the set $\{1, 2, \dots, k\}$, and labels must strictly decrease on any path from the root to a leaf. Let $G_{n,k}$ denote this count for given positive integers n and k . It is clear that $G_{1,1} = 1$ and $G_{n,1} = 0$ for all $n \geq 2$. Then, letting $C(n)$ denote the set of all compositions of n , we have the recurrence formula

$$G_{n,k} = G_{n,k-1} + \sum_{S \in C(n-1)} \prod_{s \in S} G_{s,k-1}, \quad (1)$$

for $k \geq 2$. The first term $G_{n,k-1}$ corresponds to the number of labellings that do not use the label k . For the second term, the root label must be k , the children of the root have subtrees with a total of $n - 1$ nodes, and each subtree must only use labels from $\{1, 2, \dots, k - 1\}$. Note that (1) is valid for $n = 1$ as well (with the summation equal to 1), since $C(0) = \emptyset$. The sequence $G_{n,k}$ has two parameters, which suggests the use of a bivariate generating function in its analysis (see, e.g., [12] for a detailed account

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of methods related to multivariate generating functions). However we found that the nature of our specific recurrence made it easiest to work with a sequence of single-variable generating functions instead. For $k \geq 1$, let $G_k(z)$ be the generating function

$$G_k(z) = \sum_{n=1}^{\infty} G_{n,k} z^n.$$

Immediately we see that $G_1(z) = z$, and from the recurrence (1), we have

$$G_k(z) = G_{k-1}(z) + \frac{z}{1 - G_{k-1}(z)}, \quad (2)$$

for $k \geq 2$. For any fixed k the function $G_k(z)$ is rational, with nonnegative integers $G_{n,k}$ as coefficients. Hence by Pringsheim's theorem [4], if the radius of convergence of $G_k(z)$ is R_k , then R_k is a singularity of the function $G_k(z)$. From the formula (2), it is clear that any pole of $G_{k-1}(z)$ as well as any solution z to $G_{k-1}(z) = 1$ is a pole of $G_k(z)$.

For convenience, we define $S_k(z) = 1 - G_k(z)$. The functions $S_k(z)$ satisfy the recurrence

$$S_k(z) = S_{k-1}(z) - \frac{z}{S_{k-1}(z)}, \quad (3)$$

with $S_1(z) = 1 - z$. We define z_k^* to be the smallest positive real root of $S_k(z)$; hence we must have $S_k(z) > 0$ for $z \in [0, z_k^*)$. Furthermore, the formula (3) implies that $S_k(z) \leq S_{k-1}(z)$ for $z \in [0, z_{k-1}^*)$, so z_k^* is a nonincreasing sequence of positive numbers. We now give a lower bound for z_k^* and show that $S_k(z)$ is small at a point close to this lower bound.

Lemma 1.1. *For every $k \geq 1$,*

$$z_k^* \geq k - \sqrt{k^2 - 1}, \quad (4)$$

and

$$S_k\left(\frac{1}{2k}\right) \leq \left(\frac{1}{4k}\right)^{1/4}. \quad (5)$$

Proof. Squaring both sides of (3) yields

$$S_k(z)^2 - S_{k-1}(z)^2 = -2z + \frac{z^2}{S_{k-1}(z)^2}, \quad (6)$$

and by telescoping, we have

$$\begin{aligned} S_k(z)^2 &= (1 - z)^2 + \sum_{j=2}^k (S_j(z)^2 - S_{j-1}(z)^2) \\ &= (1 - z)^2 - 2(k - 1)z + \sum_{j=2}^k \frac{z^2}{S_{j-1}(z)^2} \\ &= 1 - 2kz + z^2 + \sum_{j=1}^{k-1} \frac{z^2}{S_j(z)^2}. \end{aligned} \quad (7)$$

Thus the lower bound $S_k(z)^2 \geq 1 - 2kz + z^2$ is immediate, and since $1 - 2kz + z^2$ is positive for $0 \leq z < k - \sqrt{k^2 - 1}$, we must have $z_k^* \geq k - \sqrt{k^2 - 1}$. This proves the first claim. From the bound just proved, we find that $1/(2k) \in [0, z_k^*]$, so by our earlier observation, the sequence $S_j(1/(2k))$ is nonincreasing in j . Moreover, we have $S_j(z) \leq S_j(0) = 1$ for all $j \geq 1$; from this we obtain

$$\begin{aligned} S_k \left(\frac{1}{2k} \right)^2 &= 1 - 2k \left(\frac{1}{2k} \right) + \left(\frac{1}{2k} \right)^2 + \sum_{j=1}^{k-1} \frac{1}{4k^2 S_j(1/(2k))^2} \\ &\leq \frac{1}{4k^2} + \frac{k-1}{4k^2 S_k(1/(2k))^2} \\ &\leq \frac{1}{4k S_k(1/(2k))^2}. \end{aligned} \quad (8)$$

Solving the inequality gives $S_k(1/(2k)) \leq (1/(4k))^{1/4}$, as desired. \square

Next, we derive an upper bound for z_k^* .

Lemma 1.2. *For all $k \geq 1$,*

$$z_k^* \leq \frac{1}{2k(1 - (1/(4k))^{1/4})}. \quad (9)$$

Proof. First we observe that S_k is a concave function on $[0, z_k^*]$. This follows from the fact that G_k is a power series with positive coefficients and no constant term, so $S_k = 1 - G_k$ has constant term 1 and all other coefficients negative. Moreover, as G_k is a rational function, it is analytic within its radius of convergence, hence all of its derivatives are well-defined and negative on $[0, z_k^*]$. Concavity of S_k gives us

$$S_k \left(\frac{1}{2k} \right) \geq \frac{1}{2kz_k^*} S_k(z_k^*) + \left(1 - \frac{1}{2kz_k^*} \right) S_k(0) = 1 - \frac{1}{2kz_k^*}, \quad (10)$$

and applying Lemma 1 now yields

$$\left(\frac{1}{4k} \right)^{1/4} \geq 1 - \frac{1}{2kz_k^*}, \quad (11)$$

and the result follows upon rearranging. \square

We can now describe the first-order asymptotic behaviour of $G_{n,k}$.

Theorem 1.3. *Let $G_{n,k}$ denote the number of planted plane trees with decreasing labels. Then for all $k \geq 1$, there exist real numbers c_k and α_k such that*

$$G_{n,k} = c_k \alpha_k^n (1 + o(1)), \quad (12)$$

as $n \rightarrow \infty$, where

$$2(k-1) \left(1 - \frac{1}{\sqrt{2(k-1)}^{1/4}} \right) \leq \alpha_k \leq k-1 + \sqrt{(k-1)^2 - 1}. \quad (13)$$

In particular, $\alpha_k = 2k + o(k)$ as $k \rightarrow \infty$.

Proof. As we did previously, for all $k \geq 1$ let z_k^* denote the solution to $G_k(z^k) = 1$. We know that for $k \geq 2$, $G_k(z)$ has only one pole on the domain $|z| \leq z^*k - 1$, namely, z_{k-1}^* . We claim that this is a simple pole. Since $G_1(z) = z$ and

$$G_k(z) = \frac{G_{k-1}(z) - G_{k-1}(z)^2 + z}{1 - G_{k-1}(z)}, \quad (14)$$

for $k \geq 2$, we see that $G_k(z)$ is a rational function. Thus

$$\lim_{z \rightarrow z_{k-1}^*} (z - z_{k-1}^*)G_k(z) = \frac{G_{k-1}(z_{k-1}^*) - G_{k-1}(z_{k-1}^*)^2 + z_{k-1}^*}{-G'_{k-1}(z_{k-1}^*)} = \frac{z_{k-1}^*}{-G'_{k-1}(z_{k-1}^*)}. \quad (15)$$

The function $G_{k-1}(z)$ is analytic on the domain $|z| \leq z^{k-1}$ and its power series has nonnegative coefficients. Since the constant term in the power series $G'k - 1(z)$ is

$$[z]G_{k-1}(z) = G_{1,k-1} = k - 1 > 0, \quad (16)$$

the above limit is finite. This means that z^{k-1} is a pole of order 1 of the function $G_k(z)$. Letting $\alpha_k = 1/z^*k - 1$, by a standard result on the coefficient asymptotics of rational functions, we have

$$G_{n,k} = c_k \alpha_k^n (1 + o(1)), \quad (17)$$

where c_k is a constant depending on k only. The claimed bounds on α_k follow from the two previous lemmas. \square

We also note the following explicit upper bound. As $G_k(z_k^*) = 1$, we immediately have

$$G_{n,k} \leq \left(\frac{1}{z_k^*}\right)^n = \alpha_{k+1}^n.$$

This is weaker than (17), but only slightly so, as $\alpha_{k+1}/\alpha_k \rightarrow 1$ as $k \rightarrow \infty$.

The regular leaning tree of order k . Consider the sequence T_0, T_1, T_2, \dots of trees defined recursively as follows. Let T_0 be a single root node with no children, and for $k \geq 1$, we define T_k to be the tree with a root node having k children whose subtrees are $T_{k-1}, T_{k-2}, \dots, T_0$. We shall call T_k the regular leaning tree of order k . For all $k \geq 0$, the tree T_k has 2^k nodes. The following algorithm gives a mapping from the set of closed walks of length $2n$ starting at the root of T_k and n -node planted plane trees with root label $k + 1$ and decreasing labels.

Algorithm 1.4 (Algorithm P). (*Build planted plane tree*). Given a closed walk

$$\sigma = (u_0, u_1, \dots, u_{2n}),$$

of length $2n$ in T_k , this algorithm outputs a planted plane tree labelled with positive integers.

- P1. [Initialize.] Set $i \leftarrow 0$ and initialize the tree P with a root node v and set $\text{LABEL}(v) \leftarrow k + 1$.

- P2. [Child.] If u_{i+1} is the parent of u_i , go to step P3. Otherwise, suppose that u_{i+1} is the root of a subtree isomorphic to T_j for some $j < \text{LABEL}(v)$. Append a child with label $j + 1$ to v and update v to point to this child. Go to step P4.
- P3. [Parent.] Set $v \leftarrow \text{PARENT}(v)$.
- P4. [Loop.] Increment i by one. If $i < 2n$, go to step P2; otherwise terminate the algorithm with the tree P as output.

The root of the output planted plane tree has label $k + 1$, and every time we move downward in T_k along the path σ and encounter the root of T_j for some $j \leq k$, we append a node with label $j + 1$. This implies that the output of Algorithm P is a planted plane tree with decreasing labels and root label $k + 1$. We also know that this output tree has $n + 1$ nodes, since we start with one root node, and in the walk σ , half of the $2n$ edges must go down in the tree and half must go up (to return to the root), and we add a node to P when (and only when) going down. The tree P is built up in depth-first preorder, so it is easy to write an algorithm that recovers the walk from a tree P output by Algorithm P.

Algorithm 1.5 (Algorithm W). (*Build walk in T_k*). Given a planted plane tree P with decreasing labels and root label $k + 1$, we build a walk σ starting at the root in T_k . Suppose we have a function $\text{NEXT}(v)$ of getting the node that follows a given node $v \in P$ in a depth-first traversal of P (in this traversal, nodes may be visited multiple times).

- W1. [Initialize.] Let u_0 be the root of T_k . Set $i \leftarrow 0$ and let v be the root of P .
- W2. [Child.] Let $w \leftarrow \text{NEXT}(v)$. If w is the parent of v , go to step W3. Otherwise, let u_{i+1} be the child of u_i that is the root of the subtree isomorphic to T_j , where $j = \text{LABEL}(w) - 1$. Go to step W4.
- W3. [Parent.] Set $u_{i+1} \leftarrow \text{PARENT}(u_i)$.
- W4. [Loop.] Set $v \leftarrow w$ and increment i by one. (An invariant we have maintained is that u_i is the root of a subtree isomorphic to T_j , where $j = \text{LABEL}(v) - 1$. This makes step W2 possible in the next iteration.) If $i < 2n$, go to step W2; otherwise, terminate the algorithm with output $\sigma = (u_0, u_1, \dots, u_{2n})$.

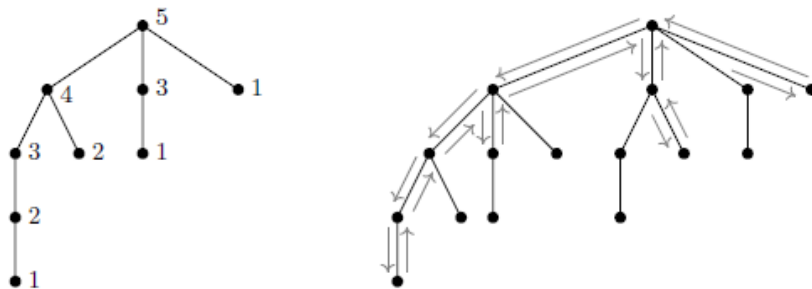


Fig. 1. A planted plane tree with root label 5 and its corresponding walk in T_4

An example of a tree P and its corresponding walk in T_k is illustrated in Figure 1. The parallel structures of Algorithms P and W make it clear that if Algorithm P terminates with output P upon being given input σ , then Algorithm W returns the walk σ upon the input P . We have thus furnished a bijective proof of the following theorem.

Theorem 1.6. *Let n and k be positive integers. The number $W_{2n}(T_k)$ of closed paths in T_k of length $2n$ that begin and end at the root is equal to the number $G_{n+1,k+1} - G_{n+1,k}$ of $(n+1)$ -node planted plane trees with decreasing labels and root label equal to $k+1$.*

The top eigenvalue of a regular leaning tree. Let $\Gamma = (V, E)$ be a connected graph, let $A = A(\Gamma)$ be its adjacency matrix, and let $\lambda_1(A)$ denote the largest eigenvalue of A . By the trace method, we have

$$\begin{aligned} \lambda_1(A) &= \lim_{n \rightarrow \infty} (\text{tr}(A^{2n}))^{1/2n} \\ &= \lim_{n \rightarrow \infty} \left(\max_{v \in V} W_{2n}(v, \Gamma) \right)^{1/2n} \\ &= \lim_{n \rightarrow \infty} \left(\min_{v \in V} W_{2n}(v, \Gamma) \right)^{1/2n}, \end{aligned} \quad (18)$$

where $W_{2n}(v, \Gamma)$ denotes the number of closed walks of length $2n$ in Γ starting at the vertex v . It is well known that if $\Gamma = T$ is a tree and A is its adjacency matrix, then the largest eigenvalue $\lambda_1(A)$ of A satisfies

$$\sqrt{\Delta} \leq \lambda_1(A) \leq 2\sqrt{\Delta - 1}, \quad (19)$$

where $\Delta \geq 2$ is the maximum vertex degree of T . (The lower bound is trivial and the upper bound is a result of D. Stevanović [13].) Theorems 3 and 4 together tell us that largest eigenvalue of the adjacency matrix of a leaning tree of order k (which has maximum vertex degree $k+1$) does not tend towards either of these bounds as $k \rightarrow \infty$.

Lemma 1.7. *Let $k \geq 1$ and let A_k denote the adjacency matrix of the regular leaning tree T_k . Then the largest eigenvalue $\lambda_1(A_k)$ is $\sqrt{2k + o(k)}$.*

The Ulam–Harris number. We can extend the above result to arbitrary trees as follows. We give the root the label 0, and for any node with label r and s children, we label the children $r+1, r+2, \dots, r+s$. We define the Ulam–Harris number $\text{UH}(T)$ of a planted plane tree T to be the maximum label in the tree. (There is a standard notion of the Ulam–Harris labelling of a tree (see, e.g., Section 6 of [5]), in which one assigns a vector of positive integers to each node. Our Ulam–Harris number is the maximum sum of coordinates, taken over all Ulam–Harris labels in the tree.) For an unordered tree T , we can let $\text{UH}(T)$ be the minimum of $\text{UH}(T')$ over all planted plane trees T' obtained from T by choosing orderings for the children of each node.

Theorem 1.8. *Let T be a rooted unordered tree, and let A be the adjacency matrix of T . Then $\lambda_1(A) \leq \lambda_1(A_{\text{UH}(T)})$, where $A_{\text{UH}(T)}$ is the adjacency matrix of the regular leaning tree of order $\text{UH}(T)$.*

Proof. Consider T as a labelled planted plane tree, with maximum label $\text{UH}(T)$. Replace each label j with $\text{UH}(T) - j$. Then the root has label $\text{UH}(T)$, all labels are nonnegative and decreasing both as one descends in the tree, and as one goes from left to right among siblings. Furthermore, the new label of each node is strictly greater than the number of children it has, so we can embed T into the regular leaning tree $T_{\text{UH}(T)}$, and the claim follows. \square

Let T be a tree with maximum vertex degree Δ and adjacency matrix A . Since a node and its children must all have different labels, we must have $\text{UH}(T) \geq \Delta$; the regular leaning tree of order k attains this bound with equality. Lemma 1.7 and Theorem 1.8 together supply an upper bound of roughly $\sqrt{2\text{UH}(T)}$ on $\lambda_1(A)$. In the scenario where $\text{UH}(T) < 2\Delta - 2$ (as in Figure 2, for instance), this improves upon Stevanovič's bound of $2\sqrt{\Delta - 1}$.

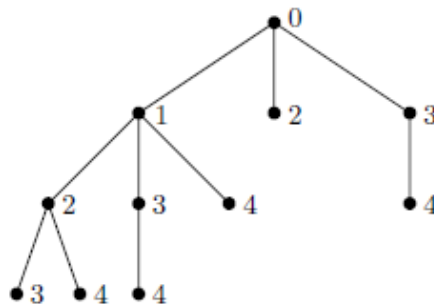


Fig. 2. A planted plane tree with Ulam–Harris number equal to 4

2. Related work

In this paper we have considered trees with decreasing labels, but in the literature it has been somewhat more common to count trees with increasing labels (by reflecting the values of the nodes, there are exactly as many increasing trees with maximum label k as there are decreasing ones). There is a classical bijection between permutations of $1, \dots, n$ and increasing binary trees on n nodes using each label from 1 through n exactly once. A 2020 paper of Bodini et al. [2] relaxed the stipulation that all the labels 1 through n must appear, requiring instead that for some $1 \leq k \leq n$, all the labels 1 through k must appear (labels must still strictly increase down the tree). A later paper of Bodini et al. [3] describes a more general approach that applies to more families of trees.

In 1987, Blieberger [1] counted the number of Motzkin trees with labels that increase, but not necessarily strictly. Kemp showed in 1993 [7] that the planted plane trees labelled similarly are in bijection with monotonically extended binary trees. In 2011, Janson, Kuba and Panholzer [6] drew a link between generalized Stirling permutations and k -ary trees with (strictly) increasing labels. A generalization of labelled trees, in which nodes can receive multiple labels, was introduced in 2016 by Kuba and Panholzer [10] and this generalization is shown to imply various hook-length formulas for trees.

Other authors have considered the average shape [8] and the degree distribution [9] of

various tree families with increasing labels. The expectation and variance of the size of the ancestor tree as well as the Steiner distance of increasingly labelled trees were determined by Morris in 2004 [11].

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