ON THE LIMITING DISTRIBUTIONS OF THE TOTAL HEIGHT ON FAMILIES OF TREES

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Abstract

A symbolic-computational algorithm, fully implemented in Maple, is described, that computes explicit expressions for generating functions that enable the efficient computations of the expectation, variance, and higher moments, of the random variable 'sum of distances to the root', defined on any given family of rooted ordered trees (defined by degree restrictions). Taking limits, we confirm, via elementary methods, the fact, due to David Aldous, and expanded by Svante Janson and others, that the limiting (scaled) distributions are all the same, and coincide with the limiting distribution of the same random variable, when it is defined on labeled rooted trees.

Maple Packages and Sample Input and Output Files

This article is accompanied by Maple packages, `TREES.txt`, and `THS.txt`, and several input and output files available from the front of this article
`http://www.math.rutgers.edu/~zeilberg/mamarim/mamarimhtml/otrees.html`.

Background

While many natural families of combinatorial random variables, X_n, indexed by a positive integer n, (for example, tossing a coin n times and noting the number of heads, or counting the number of occurrences of a specific pattern in an n-permutation) have different expectations, μ_n, and different standard deviations, σ_n, and (usually) largely different asymptotic expressions for these, yet the centralized and scaled versions, $Z_n := \frac{X_n - \mu_n}{\sigma_n}$, very often, converge (in distribution) to the standard normal distribution whose probability density function is famously $\frac{1}{\sqrt{2\pi}}exp(-\frac{x^2}{2})$, and whose moments are $0, 1, 0, 3, 0, 5, 0, 15, 0, 105, \ldots$. Such sequences of random variables are called *asymptotically normal*. Whenever this is **not** the case, it is a cause for excitement [Of course, excitement is in the eyes of the beholder]. One celebrated case (see Dan Romik's [13] masterpiece for an engaging and detailed description) is the random variable 'largest increasing subsequence', defined on the set of permutations, where the intriguing *Tracy-Widom distribution* shows up.

Other, more recent, examples of *abnormal* limiting distributions are described in [18], [3], [4], and [5].

In this article we consider, from an elementary, explicit, *symbolic-computational*, viewpoint, the random variable 'sum of distances to the root', defined over an *arbitrary* family of ordered rooted trees defined by degree restrictions. For analysis of this statistic over uniformly chosen random rooted trees, see [14] and [15]. The asymptotic behavior of this statistic for that uniform distribution of random rooted trees is given in [16].

It turns out that the families of trees considered in this paper are special cases of Galton-Watson trees. These have been studied extensively by continuous probability theorists for many years, with a nice, comprehensive introduction given by Janson in [9]. For an analysis of unlabelled Galton-Watson trees, see the work Wagner [17]. In particular, they are trees that are determined by determining the number of children that every node has by independently sampling some fixed distribution with expected value at most 1. Like the trees considered here (described below), they are also types of Galton-Watson trees. It was shown in [1], [2], and [11] that all Galton-Watson generated from a finite variance distribution of vertex degrees followed the same distribution as the area under a Brownian excursion, also a topic well studied in advanced probability theory. In particular, Janson, in section 14 of [7], presents a complicated infinite sum which converges to this distribution originally discovered by Darling (1983). Asymptotic analysis of mean, variance, and higher moments for Galton-Watson trees can be found in [10].

All these authors used *continuous*, advanced, probability theory, that while very powerful, only gives you the limit. We are interested in *explicit* expressions for the first few moments themselves, or failing this, for explicit expressions for the generating functions, for *any* family of rooted ordered trees given by degree restrictions. In particular, we study in detail the case of *complete binary trees*, famously counted by the Catalan numbers.

We proceed in the same vein as in [4]. In that article, the random variable 'sum of the distances from the root', defined on the set of *labelled rooted trees* on n vertices, was considered, and it was shown how to find explicit expressions for any given moment, and the first 12 moments were derived, extending the pioneering work of John Riordan and Neil Sloane ([12]), who derived an explicit formula for the expectation. The exact and approximate values for the *limits*, as $n \to \infty$, of α_3

(the *skewness*), α_4 (the *kurtosis*), and the higher moments through the ninth turn out to be as follows.

$$\alpha_3 = \frac{\left(6\,\pi - \frac{75}{4}\right)\sqrt{3}\sqrt{\frac{\pi}{10-3\,\pi}}}{10-3\,\pi} = 0.7005665293596503\ldots \quad ,$$

$$\alpha_4 = \frac{-189\,\pi^2 + 315\,\pi + 884}{7\,(10-3\,\pi)^2} = 3.560394897132889\ldots \quad ,$$

$$\alpha_5 = \frac{\left(36\,\pi^2 + \frac{75}{2}\,\pi - \frac{105845}{224}\right)\sqrt{3}\sqrt{\frac{\pi}{10-3\,\pi}}}{(10-3\,\pi)^2} = 7.2563753582799571\ldots \quad ,$$

$$\alpha_6 = \frac{15}{16016}\,\frac{-144144\,\pi^3 - 720720\,\pi^2 + 3013725\,\pi + 2120320}{(10-3\,\pi)^3}$$
$$= 27.685525695770609\ldots \quad ,$$

$$\alpha_7 = \frac{\left(162\,\pi^3 + \frac{6615}{4}\,\pi^2 - \frac{103965}{32}\,\pi - \frac{101897475}{9152}\right)\sqrt{3}\sqrt{\frac{\pi}{10-3\,\pi}}}{(10-3\,\pi)^3}$$
$$= 90.0171829093603301\ldots \quad ,$$

$$\alpha_8 = \frac{3}{2586584}\,\frac{-488864376\,\pi^4 - 8147739600\,\pi^3 - 455885430\,\pi^2 + 86568885375\,\pi + 32820007040}{(10-3\,\pi)^4}$$
$$= 358.80904151261251\ldots \quad ,$$

$$\alpha_9 = \frac{\left(648\,\pi^4 + 15795\,\pi^3 + \frac{591867}{16}\,\pi^2 - \frac{461286225}{2288}\,\pi - \frac{188411947088175}{662165504}\right)\sqrt{3}\sqrt{\frac{\pi}{10-3\,\pi}}}{(10-3\,\pi)^4}$$
$$= 1460.7011342971821\ldots \quad .$$

(Note that when the moments are not centralized, the expressions are simpler, but we prefer it this way).

This Article

In this article we extend the work of [4] and treat infinitely many other families of trees. For any given set of positive integers, S, we will have a 'sample space' of all ordered rooted trees where a vertex may have no children (i.e. be a *leaf*) or it **must** have a number of children that belongs to S. If $S = \{2\}$ we have the case of *complete binary trees*.

For each such family, defined by S, we will show how to derive explicit expressions for the generating functions of the numerators of the straight moments, from which one can easily get many values, and very efficiently find the numerical values for the moments-about-the-mean and hence the scaled moments. For the special case of complete binary trees, we will derive explicit expressions for the first nine moments (that may be extended indefinitely), as well as explicit expressions for the asymptotics of the scaled moments, and indeed (as predicted by the above-mentioned authors) they coincide *exactly* with those found in [4] for the case of labeled rooted trees. This is a specific example of a more general statement about Galton Watson trees given in [10].

Rooted Ordered Trees

Recall that an *ordered rooted tree* is an unlabeled graph with the root drawn at the top, and each vertex has a certain number (possibly zero) of children, drawn from left to right. For any finite set of positive integers, S, let $\mathcal{T}(S)$ be the set of all rooted labelled trees where each vertex either has no children, or else has a number of children that belongs to S. The set $\mathcal{T}(S)$ has the following structure ("grammar")

$$\mathcal{T}(S) = \{\cdot\} \bigcup_{i \in S} \{\cdot\} \times \mathcal{T}(S)^i \quad .$$

Fix S, Let f_n be number of rooted ordered trees in $\mathcal{T}(S)$ with exactly n vertices. It follows immediately, by elementary generatingfunctionology, that the ordinary generating function

$$f(x) := \sum_{n=0}^{\infty} f_n \, x^n \quad ,$$

(that is, the sum of the weights of *all* members of $\mathcal{T}(S)$ with the weight $x^{NumberOfVertices}$ assigned to each tree) satisfies the **algebraic** equation

$$f(x) = x \left(1 + \sum_{i \in S} f(x)^i \right) \quad .$$

Given an ordered tree, t, define the random variable $H(t)$ to be the sum of the distances to the root of all vertices. Let H_n be its restriction to the subset of $\mathcal{T}(S)$, let us call it $\mathcal{T}_n(S)$, of members of $\mathcal{T}(S)$ with exactly n vertices. Our goal in this article is to describe a symbolic-computational algorithm that, for *any* finite set S of positive integers, *automatically* finds generating functions that enable the fast computation of the average, variance, and as many higher moments as desired. We will be particularly interested in the limit, as $n \to \infty$, of the centralized-scaled distribution, and we confirm that it is always the same as the one for rooted labelled trees found in [4] as we would expect by [10].

Let $P_n(y)$ be the generating polynomial defined over $\mathcal{T}_n(S)$, of the random variable, 'sum of distances from the root'. Define the *grand generating function*

$$F(x,y) = \sum_{n=0}^{\infty} P_n(y) x^n \quad .$$

Consider a typical tree, t, in $\mathcal{T}_n(S)$, and now define the more general *weight* by $x^{NumberOfVertices}\, y^{H(t)} = x^n\, y^{H(t)}$. If t is a singleton, then its weight is simply $x^1 y^0 = x$, but if its sub-trees (the trees whose roots are the children of the original root) are $t_1, t_2, \ldots t_i$ (where $i \in S$), then

$$H(t) = H(t_1) + \cdots + H(t_i) + n - 1 \quad ,$$

since when you make the tree t, out of subtrees $t_1, \ldots, t_i$ by placing them from left to right and then attaching them to the root, each vertex gets its 'distance to the root' increased by 1, so altogether the sum of the vertices' heights gets increased by the total number of vertices in $t_1, \ldots, t_i$ (i.e. $n-1$). Hence $F(x,y)$ satisfies the **functional equation**

$$F(x,y) = x \cdot \left(1 + \sum_{i \in S} F(xy,y)^i\right) \quad ,$$

that can be used to generate many terms of the sequence of generating polynomials $\{P_n(y)\}$.

Note that when $y = 1$, $F(x,1) = f(x)$, and we get back the algebraic equation satisfied by $f(x)$.

From Enumeration to Statistics in General

Suppose that we have a finite set, A, on which a certain numerical attribute, called *random variable*, X, (using the the language of probability and statistics) is defined.

For any non-negative integer i, let us define

$$N_i := \sum_{a \in A} X(a)^i \quad .$$

In particular, $N_0(X)$ is the number of elements of A.

The expectation of X, $E[X]$, denoted by μ, is, of course,

$$\mu = \frac{N_1}{N_0} \quad .$$

For $i > 1$, the i-th straight moment is

$$E[X^i] = \frac{N_i}{N_0} \quad .$$

The i-th *moment about the mean* is

$$m_i := E[(X-\mu)^i] = E[\sum_{r=0}^{i} \binom{i}{r} (-1)^r \mu^r X^{i-r}] = \sum_{r=0}^{i} (-1)^r \binom{i}{r} \mu^r E[X^{i-r}]$$

$$= \sum_{r=0}^{i} (-1)^r \binom{i}{r} \left(\frac{N_1}{N_0}\right)^r \frac{N_{i-r}}{N_0}$$

$$= \frac{1}{N_0^i} \sum_{r=0}^{i} (-1)^r \binom{i}{r} N_1^r N_0^{i-r-1} N_{i-r} \quad .$$

Finally, the most interesting quantities, statistically speaking, apart from the mean μ and variance m_2 are the **scaled-moments**, also known as, *alpha coefficients*, defined by

$$\alpha_i := \frac{m_i}{m_2^{i/2}} \quad .$$

Using Generating Functions

In our case X is H_n (the sum of the vertices' distances to the root, defined over rooted ordered trees in our family, with n vertices), and we have

$$N_1(n) = P_n'(1)$$

$$N_i(n) = (y\frac{d}{dy})^i P_n(y)\big|_{y=1}.$$

It is more convenient to first find the numerators of the factorial moments

$$F_i(n) = (\frac{d}{dy})^i P_n(y)|_{y=1} \quad ,$$

from which $N_i(n)$ can be easily found, using the Stirling numbers of the second kind.

Automatic Generation of Generating functions for the (Numerators of the) Factorial Moments

Let us define

$$P(X) = 1 + \sum_{i \in S} X^i \quad ,$$

then our functional equation for the grand-generating function, $F(x,y)$ can be written

$$F(x,y) = xP(F(xy,y)) \quad .$$

If we want to get generating functions for the first k factorial moments of our random variable H_n, we need the first k coefficients of the Taylor expansion, about $y=1$, of $F(x,y)$. Writing $y = 1+z$, and

$$G(x,z) = F(x, 1+z) \quad ,$$

we get the functional equation for $G(x,z)$

$$G(x,z) = x\,P(G(x+xz,z)) \quad . \qquad (FE)$$

Let us write the Taylor expansion of $G(x,z)$ around $z=0$ to order k

$$G(x,z) = \sum_{r=0}^{k} g_r(x) \frac{z^r}{r!} + O(z^{k+1}) \quad .$$

It follows that

$$G(x+xz,z) = \sum_{r=0}^{k} g_r(x+xz) \frac{z^r}{r!} + O(z^{k+1}) \quad .$$

We now do the Taylor expansion of $g_r(x+xz)$ around x, getting

$$g_r(x+xz) = g_r(x) \,+\, g_r'(x)(xz) \,+\, g_r''(x)\frac{(xz)^2}{2!} \,+\, \ldots \,+\, g_r^{(k)}(x)\frac{(xz)^k}{k!} \,+\, O(z^{k+1}) \quad .$$

Plugging all this into (FE), and comparing coefficients of respective terms of z^r for r from 0 to k we get $k+1$ equations relating $g_r^{(j)}(x)$ to each other. It is easy to see that one can express $g_r(x)$ in terms of $g_s^{(j)}(x)$ with $s < r$ (and $0 \le j \le k$) .

Using implicit differentiation, the derivatives of $g_0(x)$, $g_0^{(j)}(x)$ (where $g_0(x)$ is the same as $f(x)$), can be expressed as rational functions of x and $g_0(x)$. As soon as we get an expression for $g_r(x)$ in terms of x and $g_0(x)$, we can use calculus to get expressions for the derivatives $g_r^{(j)}(x)$ in terms of x and $g_0(x)$. At the end of the day, we get expressions for each $g_r(x)$ in terms of x and $g_0(x)$ (alias $f(x)$), and since it is easy to find the first ten thousand (or whatever) Taylor coefficients of $g_0(x)$, we can get the first ten thousand coefficients of $g_r(x)$, for all $0 \le r \le k$, and get the numerical sequences that will enable us to get very good approximations for the alpha coefficients.

The beauty is that this is all done by the computer! Maple knows calculus.

We can do even better. Using the methods described in [6], one should be able to get, *automatically*, asymptotic formulas for the expectation, variance, and as many moments as desired. Using these techniques, it may be possible to obtain expressions for the leading terms of all moments, and so show weak convergence of this distribution to a particular limiting distribution. This should be an interesting future project.

For the special case of complete binary trees, everything can be expressed in terms of Catalan numbers, and hence the asymptotic is easy, and our beloved computer, running the Maple package `TREES.txt` (mentioned above), obtained the results in the next section.

Computer-Generated Theorems About the Expectation, Variance, and First Nine Moments for the Total Height on Complete Binary Trees on n Leaves

See the output file

`http://www.math.rutgers.edu/~zeilberg/tokhniot/oTREES3.txt` .

Universality

The computer output, given in the above webpage, proved that for this case, of complete binary trees, the limits of the first nine scaled moments coincide *exactly* with those found in [4], and given above. This confirms, by *purely elementary, finitistic methods*, the universality property mentioned above. We do it for one family at a time, and only for finitely many moments, but on the other hand, we derived *explicit* expressions for the first twelve moments in the case of complete binary trees, and explicit expressions for the generating functions for the moments for other families.

Conclusion

Even more interesting than the *actual* research reported here, it the way that is was obtained. Fully automatically!

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