Galton-Watson Trees with the Same Mean Have the Same Polar Sets

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ABSTRACT

Evans (1992) defines a notion of what it means for a set B to be polar for a process indexed by a tree. The main result herein is that a tree picked from a Galton-Watson measure whose offspring distribution has mean m and finite variance will almost surely have precisely the same polar sets as a deterministic tree of the same growth rate. This implies that deterministic and nondeterministic trees behave identically in a variety of probability models. Mapping subsets of Euclidean space to trees and polar sets to capacity criteria, it follows that certain random Cantor sets are capacity-equivalent to each other and to deterministic Cantor sets. An extension to branching processes in varying environment is also obtained.

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1 Introduction

The family tree of a supercritical Galton-Watson branching process with a single progenitor is called a *Galton-Watson tree* (a formal definition is given later in this section). There is a general principle saying that Galton-Watson trees of a given mean behave similarly to "balanced" deterministic trees of the same exponential growth rate. The object of this paper is to state and prove a version of this principle under an assumption of finite variance, which is shown to be indispensable. Of course, not all behavior is the same. For example, the speed of simple random walk on a Galton-Watson tree of mean growth $m \in \mathbf{Z}$ is strictly less than on the deterministic m-ary tree (Lyons, Pemantle and Peres 1994); the Hausdorff measure of the boundary of the regular tree in its dimension is positive, while the Galton-Watson tree has zero Hausdorff measure in the same gauge (Graf, Mauldin and Williams 1988); the dimension of harmonic measure for simple random walk is strictly less on the Galton-Watson tree (Lyons, Pemantle and Peres 1994). Consequently, such a general principle must begin with a discussion of which properties of a tree one cares about, and among them, those aspects that one might expect to be the same for all Galton-Watson trees of a given mean.

Consider first some intrinsic properties. If Z_n is the number of vertices at distance n from the root, then $n^{-1} \log Z_n \to \log m$ almost surely upon nonextinction, for any offspring distribution with mean $m > 1$. If one assumes further that Z_1 is always positive and $\mathbf{E} Z_1 \log Z_1 < \infty$ then in fact $m^{-n} Z_n \to W \in (0, \infty)$ almost surely, where W is a random variable. Finer information concerning the growth of the tree is obtained by computing its Hausdorff measure and capacity with respect to arbitrary gauge functions (definitions are given in Section 2). If one thinks of trees as encoding subsets of Euclidean space via base b expansion for some $b \geq 2$, then information about which gauge functions give a Galton-Watson tree positive capacity may be translated into information about the capacity in an arbitrary gauge of a random Cantor-like subset of Euclidean space. These ideas are expanded in Sections 3 and 4.

A probabilist may be more concerned with extrinsic properties of trees, arising from the use of trees in probability models. In the study of branching processes in deterministic, varying or random environments, the tree is the family tree of the process, and one is typically concerned with the question of whether the process survives (Agresti 1975, Lyons 1992). In the study of branching random walks, the tree indexes the branching which may be deterministic or random. Typical questions are the location of the extremal particles, or whether a line of descent can remain in a specified region; see Benjamini and Peres (1994a, 1994b) for the case of deterministic branching and Kesten (1978) for random branching. The vertices of a tree may be the states of a random walk in a deterministic (e.g. Sawyer 1978) or random (Pemantle 1992; Lyons and Pemantle 1992) environment; an important question here concerns recurrence or transience of the random walk, which depends on the capacity of the tree in certain gauges (Lyons 1990, 1992). First-passage percolation on a tree is considered in Lyons and Pemantle (1992), in Pemantle and Peres (1994a) and in Barlow, Pemantle and Perkins (1993); here the important questions are the time to reach infinity or the rate of growth of the cluster before infinity is reached. We now define a notion of *polar sets* sufficiently broad to encompass most of the properties mentioned in the two preceding paragraphs.

Suppose Γ is an infinite tree with root ρ. Let $\{X(v)\}$ be a collection of IID real random variables indexed by the vertices v of Γ. Let $B \subseteq \mathbb{R}^\infty$ be any closed subset. One may then ask for the probability $P(\Gamma; B)$ of the event $A(\Gamma; B)$, that there exists an infinite, non-self-intersecting path $\rho, v_1, v_2, \ldots$, for which $(X(v_1), X(v_2), \ldots) \in B$. Strictly speaking, $P(\Gamma; B)$ depends on the common distribution F of the $X(v)$ as well as on Γ and B, but we write $P(\Gamma; B; F)$ only when the dependence on F is important. Similarly, the event $A(\Gamma; B)$ will be written as $A(\Gamma; B; X)$ only when stressing dependence on the family $\{X(\sigma)\}$. Evans (1992) calls such a collection of random variables a *tree-indexed process*, viewing it as an $\mathbb{R}^\infty$-valued random field indexed by the space $\partial\Gamma$ of infinite, non-self-intersecting paths from the root of Γ. The process has also been called *target percolation* in Pemantle and Peres (1994b) and *random labelling* in Lyons (1992).

Evans (1992) calls a set B *polar* for the tree Γ if $P(\Gamma; B) = 0$; he attributes the question of which sets are polar to Dubins and Freedman (1967). We define trees $\Gamma^{(1)}$ and $\Gamma^{(2)}$ to be *equipolar* if for every set B, it is polar for $\Gamma^{(1)}$ if and only if it is polar for $\Gamma^{(2)}$. To illustrate how this relates to the previously mentioned aspects of trees, here are four examples showing that equipolar trees behave similarly with respect to the above geometric and probabilistic criteria.

1. First-passage percolation: Think of $X(v)$ as the passage time across the edge between v and its parent. An explosion occurs if infinity is reached in finite time. This happens with probability $P(\Gamma; B)$, where B is the set of summable sequences. (Technically, in order to keep the sets closed, one lets B_k be the set of sequences with sum at most k, and $P(\Gamma; B)$ is then the increasing limit of $P(\Gamma; B_k)$). Pemantle and Peres (1994a) determine which trees Γ in a certain class have $P(\Gamma; B) = 0$. If two trees are equipolar, then explosions occur on both or neither. If no explosion occurs, one can ask for the rate at which the fastest passage occurs. If we let

$$B = \{(x_1, x_2, \ldots) : \sum_{j=1}^{n} x_j \geq f(n) \text{ for all } n\}, \tag{1}$$

then $A(\Gamma; B)$ is the event of passage at rate at least f; this is discussed in Lyons and Pemantle (1992). Equipolar trees have the same passage rate. One may also let the means of the passage times vary by considering $\sum g(j)x_j$ in (1) instead of $\sum x_j$; this is done in Barlow, Pemantle and Perkins (1993).

2. Branching random walk: Let Γ be a random tree, chosen from some Galton-Watson measure, and conditional on Γ let $\{X(v)\}$ be IID random vectors indexed by the vertices of Γ. Think of the tree Γ as the family tree of some species, and the vector $X(v)$ as the spatial displacement of the individual v from its parent. Si Levin (personal communication) considered a model in which $C \subseteq \mathbb{R}^n$ represents a region inhospitable to procreation. Let B be the set of sequences of vectors $(x_1, x_2, \ldots)$ such that $\sum_{j=1}^{n} x_j \notin C$ for all n. Then $A(\Gamma; B)$ is the event that the family line of the species survives and so the survival probability is $\mathbf{E}P(\Gamma; B)$. If two trees are equipolar, one survives with positive probability if and only if the other does. For branching random walks in one dimension, one may ask for escape envelopes, i.e. for which functions f there is with positive probability some line of descent of particles that has ordinate at least $f(n)$ at every time n (see Kesten 1978 and Pemantle and Peres 1994b). This event may be written as $A(\Gamma; B)$ for an appropriate B and therefore equipolar trees have the same escape envelopes.

3. Branching random walk continued: For one-dimensional branching random walks, the maximum displacement Y_n over all individuals in the n^{th} generation is a quantity of interest. In Derrida and Spohn (1988) the behavior of Y_n on a binary tree Γ is studied, whereas Bramson

(1978) considers Y_n on a random tree, Γ', which records the branching in a continuous-time branching random walk. The notion of polarity described above is not *directly* applicable to the asymptotics of Y_n, since the rightmost particles at different generations need not lie on the same line of descent (see the discussion of "cloud speed" in Benjamini and Peres (1994a), Theorem 1.2). To study Y_n anyway we consider, instead of *one* set B, the sequence of sets

$$B_n = \{(x_1, x_2, \dots) : \sum_{k=1}^{n} x_k \geq f(n)\}$$

for some fixed function f. The comparison inequalities needed in this case appear slightly stronger than equipolarity : There should be a constant M for which

$$M^{-1} < P(\Gamma; B)/P(\Gamma'; B) < M$$

for *all* target sets B (see Remark 1 following Theorem 1.1). If these uniform estimates hold, then taking $f(n)$ to be a quantile for the distribution of the maximal displacement of branching walk on the n^{th} level of Γ, shows that the distribution of Y_n about its median is tight on Γ if and only if it is tight on Γ'. Also, these estimates imply that $P(\Gamma; B_n) \to 0$ if and only if $P(\Gamma'; B_n) \to 0$, so the Y_n fall between the same envelopes whether the branching is governed by Γ or by Γ'.

4. Capacity-equivalence: Let B be a product set, so there are sets $A_1, A_2, \dots$ such that $(x_1, x_2, \dots) \in B$ if and only if $x_i \in A_i$ for all i. It is shown in Lyons (1992) that $P(\Gamma; B) > 0$ if and only if Γ has positive capacity with respect to the gauge $f(n) = \prod_{i=1}^{n} \mathbf{P}(A_i)^{-1}$. Thus equipolar trees are *capacity-equivalent*, meaning that they have positive capacity for precisely the same gauge functions. In Section 4 we expand on this example.

Evans (1992) obtains exact capacity criteria for a set B to be polar in the case where Γ is a homogeneous tree. Lyons (1992) has criteria for general trees (see Theorem 5.3 below), but these are harder to apply directly to concrete problems, since they involve the capacity of a certain "product tree", rather than of the target set B itself. Still, his results are the basis for the present work.

After homogeneous trees, the next most basic model (and one that is probably more widely applied) is the Galton-Watson tree. To make the notion of a Galton-Watson tree precise, let $q_1, q_2, q_3 \ldots$ be nonnegative real numbers summing to one, and let $\mathbf{P}_q$ be the probability measure on infinite rooted trees under which the numbers of children $N(v)$ of each vertex v are IID, with common distribution $\mathbf{P}(N(v) = n) = q_n$. Notice that there is no q_0, so every line of descent is infinite. (This assumption loses no generality : For a supercritical Galton-Watson tree with $q_0 > 0$, the subtree consisting of all infinite lines of descent is itself distributed as another Galton-Watson tree with $q_0 = 0$ (cf. Athreya and Ney 1972, p. 16) , and the events $A(\Gamma; B)$ we are considering are determined by this subtree.) We assume throughout that $q_1 \neq 1$, but leave open the possibility that $q_n = 1$ for some $n > 1$. Thus our results hold for deterministic homogeneous trees other than the unary tree. Throughout the paper we let m denote the mean of the offspring distribution:

$$m \stackrel{def}{=} \sum_n n q_n > 1.$$

The measures $\mathbf{P}_q$ for different distributions q are mutually singular, though we have seen that they share certain attributes if m is held constant. We now state this as a theorem, in the case where the variances of the offspring distributions are finite.

Theorem 1.1 *Let q and q' be offspring distributions with $\sum n q_n = m = \sum n q'_n$. Assume that $q_0 = q'_0 = 0$ and that $\sum n^2 q_n$ and $\sum n^2 q'_n$ are both finite. Then the $\mathbf{P}_q \times \mathbf{P}_{q'}$ probability of picking two equipolar trees is 1.*

Remarks:

1. In fact the proof will show something stronger, namely that when Γ and Γ' are picked respectively from $\mathbf{P}_q$ and $\mathbf{P}_{q'}$, then $\sup_{B,F} P(\Gamma; B; F)/P(\Gamma'; B; F) < \infty$ almost surely. In fact it is equivalent to state this for F uniform on $[0, 1]$.

2. Observe that the theorem is proved with the quantifiers in the strongest order: for a.e. pick of a tree-pair from $\mathbf{P}_q \times \mathbf{P}_{q'}$, *every* target set B has the property that it is polar for both trees or for neither.

3. The idea behind Theorem 1.1 is that a Galton-Watson tree is $\mathbf{P}_q$-almost surely equipolar to a deterministic regular "tree" of the same growth. When m is an integer, this is just the m-ary tree, but when m is nonintegral, it is a virtual tree, in the sense of Pemantle and Peres (1994b). In this case, one may still find a deterministic tree to which these Galton-Watson trees are almost surely equipolar. In fact, the proof of this theorem constructs one such tree (immediately following Lemma 5.5).

4. Immediate corollaries corresponding to the four examples above are that finite-variance Galton-Watson trees of the same mean have the same gauge functions for positive capacity, the same surviving branching random walks and the same escape rate for first-passage percolation; also, due to Remark 1, the binary branching random walks of Derrida and Spohn (1988) and the randomly branching walks of Bramson (1978) have the same growth of the maximal displacement and the same tightness or non-tightness of the distribution of the maximum displacement about its median.

5. The assumption of finite variance cannot be dropped. Pemantle (1994) proves:

Theorem 1.2 *Let q and q' be offspring distributions function with mean m. Assume that q has finite variance but q' does not. Then there exists a product set B (as in Example 4) such that if the pair (Γ, Γ') is picked from $\mathbf{P}_q \times \mathbf{P}_{q'}$, then with probability 1*

$$P(\Gamma; B) > 0 = P(\Gamma'; B).$$

The remainder of the paper is organized as follows. The next section gives the notation for trees, defines capacities and proves a key lemma. Section 3 compares capacities on trees with capacities in Euclidean space; this is not needed for the proof of Theorem 1.1, but is used in the geometrical application described at the end of Section 4. Section 4 proves a special case of Theorem 1.1, namely the capacity-equivalence of Galton-Watson trees with finite variances and equal means. Although Theorem 1.1 is proved independently and implies this special case, the argument is much simpler when one is only concerned with capacity-equivalence, so the separate proof is given, along with an application to random Cantor sets. The full statement of

Theorem 1.1 is proved in Section 5. In Section 6 we discuss extensions to branching processes in varying environments (BPVE's). Section 7 presents unsolved problems.

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2 Notation and preliminary lemmas

Let Γ be a tree with root ρ. Throughout the paper, all trees are either infinite and have no leaves (vertices of degree one), or are finite of height N with no leaves except at distance N from the root. If Γ has height $N < \infty$ then the set B in the quantity $P(\Gamma; B)$ must be a subset of $\mathbb{R}^N$ rather than $\mathbb{R}^\infty$. All trees herein are also assumed to be locally finite. Let $|\sigma|$ denote the distance from σ to the root ρ, i.e. the number of edges on the unique path connecting σ to ρ. Let $\Gamma_n = \{\sigma : |\sigma| = n\}$ denote the n^{th} level of Γ. Let $\partial\Gamma$ denote the set of infinite non-self-intersecting paths from ρ; $\partial\Gamma$ is typically uncountable. If σ and τ are vertices of Γ, write $\sigma \leq \tau$ if σ is on the path connecting ρ and τ. Let $\sigma \wedge \tau$ denote the greatest lower bound for σ and τ; pictorially, this is where the paths from ρ to σ and τ diverge. If $x, y \in \partial\Gamma$, extend this notation by letting $x \wedge y$ be the greatest vertex in both x and y. This completes the basic notation for trees, and we turn to the notation for capacities.

A flow on Γ is a nonnegative function θ on the vertices of Γ with $\theta(\sigma)$ equal to the sum over children τ of σ of $\theta(\tau)$ for all σ. Let θ be a finite measure on $\partial\Gamma$. This induces a flow, also called θ, defined by $\theta(\sigma) := \theta\{y \in \partial\Gamma : \sigma \in y\}$. If $\theta(\rho) = 1$, then θ is called a unit flow. Conversely, every flow on Γ defines a measure on $\partial\Gamma$; the notions are thus equivalent but we find it helpful to keep both viewpoints in mind. Let $K : \partial\Gamma \times \partial\Gamma \to \mathbb{R}$ be a nonnegative function. Define the *energy* of the measure θ with respect to the kernel K by the formula

$$\mathcal{E}_K(\theta) = \int\int K(x, y)\, d\theta(x)\, d\theta(y). \tag{2}$$

When $K(x, y) = f(|x \wedge y|)$ for some positive, increasing function f, we often write $\mathcal{E}_f$ instead of

$\mathcal{E}_K$. Define the capacity of a subset $E \subseteq \partial\Gamma$ with respect to the kernel K to be the reciprocal of the infimum of energies $\mathcal{E}_K(\theta)$ as θ ranges over all unit flows supported on E:

$$\mathrm{Cap}_K(E) = [\inf\{\mathcal{E}_K(\theta) : \theta(E) = 1\}]^{-1}. \tag{3}$$

When E is all of $\partial\Gamma$, we write $\mathrm{Cap}(\Gamma)$ in place of $\mathrm{Cap}(\partial\Gamma)$. Write Cap_f for Cap_K when $K(x,y) = f(|x \wedge y|)$. If $f(n) \uparrow \infty$ as $n \to \infty$ with $f(-1) \stackrel{def}{=} 0$, then the energy of the measure θ may be computed from the corresponding flow as follows.

$$\begin{aligned}
\mathcal{E}_f(\theta) &= \int\int f(|x \wedge y|) d\theta(x) d\theta(y) \\
&= \int\int \sum_{\sigma \leq x \wedge y} (f(|\sigma|) - f(|\sigma| - 1)) d\theta(x) d\theta(y) \\
&= \sum_{\sigma \in \Gamma} (f(|\sigma|) - f(|\sigma| - 1)) \int\int \mathbf{1}_{\{x,y \geq \sigma\}} d\theta(x) d\theta(y) \\
&= \sum_{\sigma \in \Gamma} (f(|\sigma|) - f(|\sigma| - 1)) \theta(\sigma)^2. \qquad (4)
\end{aligned}$$

Theorem 1.1 is proved in two pieces. The first is a generalization of the following fact; the general version is stated and proved in Lemma 5.4.

Fact 2.1 *Assume that $m > 1$ is an integer and let Γ be any tree whose boundary supports a probability measure θ with*

$$\sum_{\sigma \in \Gamma_n} \theta(\sigma)^2 \leq C_\theta m^{-n}$$

for some constant C_θ and all n. Then

$$P(\Gamma; B) \geq (8C_\theta)^{-1} P(\Gamma^{(m)}; B),$$

where $\Gamma^{(m)}$ is the regular m-ary tree, each of whose vertices has m children.

We end this section with a statement and proof of the second, more elementary lemma. A different proof, valid in greater generality, is given in Section 6 (Lemma 6.2).

Lemma 2.2 *Let q be an offspring distribution function with mean m and second moment $V < \infty$. If Γ is picked from $\mathbf{P}_q$ then there exist almost surely a unit flow U on Γ and a random $C_U < \infty$ such that for all n,*

$$\sum_{\sigma \in \Gamma_n} U(\sigma)^2 \leq C_U m^{-n}.$$

To prove this, first record the following strong law of large numbers for exponentially growing blocks of identically distributed random variables, independent within each block. The proof is omitted.

Proposition 2.3 *Let $\{h(n)\}$ be a random sequence of positive integers and let F be a distribution on the reals with finite mean, β. Let $\{X_{n,k} : k \leq h(n)\}$ be a family of random variables such that for each n, the conditional joint distribution of $\{X_{n,k} : 1 \leq k \leq h(n)\}$ given $h(1), \ldots, h(n)$ is $F^{h(n)}$, i.e., $h(n)$ IID picks from F. (Note that for $n \neq n'$ the variables $X_{n,k}$ and $X_{n',k'}$ may be dependent.) Let G be the event $\{\liminf_{n\to\infty} h(n+1)/h(n) > 1\}$. Then*

$$\lim_{n\to\infty} \mathbf{1}_G \left(\beta - \frac{1}{h(n)} \sum_{k=1}^{h(n)} X_{n,k} \right) = 0 \ a.s., \tag{5}$$

as $n \to \infty$. In other words, the averages over k of $\{X_{n,k}\}$ converge to $\mathbf{E}X_{1,1}$ almost surely on the event that the sequence h is lacunary. $\square$

Proof of Lemma 2.2: The flow U will be the limit uniform flow, constructed as the weak limit as $n \to \infty$ of of flows that assign weight $|\Gamma_n|^{-1}$ to each $\sigma \in \Gamma_n$. Begin with some facts about the limit of the L^2-bounded martingale $m^{-n}|\Gamma_n|$ which may be found in Athreya and Ney (1972).

The random variable

$$W = \lim_{n\to\infty} m^{-n}|\Gamma_n|$$

is almost surely well-defined, positive and finite, with $\mathbf{E}W^2 = 1 + \mathrm{Var}(Z_1)/(m^2-1)$. Similarly, for each $\sigma \in \Gamma$ the random variable $W(\sigma)$ defined by

$$W(\sigma) = \lim_{n\to\infty} m^{|\sigma|-n} |\{\tau \in \Gamma_n : \tau \geq \sigma\}|$$

has the same distribution as W. From the definition of W one obtains directly that for each n, $W = m^{-n} \sum_{\sigma \in \Gamma_n} W(\sigma)$. Let G be the distribution of W; then it is easy to see that conditional on $|\Gamma_j|$ for $j \leq n$, the joint distribution of $W(\sigma)$ for $\sigma \in \Gamma_n$ is given by $G^{|\Gamma_n|}$, i.e. the values are conditionally IID with common distribution G. For future use, define

$$A_\Gamma = \sup_n m^{-n} |\Gamma_n| \tag{6}$$

and note that $A_\Gamma \in (0, \infty)$ almost surely. Observe also that $\liminf |\Gamma_{n+1}|/|\Gamma_n| > 1$ almost surely.

Define

$$U(\sigma) = \frac{W(\sigma)}{\sum_{|\tau|=|\sigma|} W(\tau)}.$$

It follows from the above observations that U is well-defined. Let $h(n) = |\Gamma_n|$ and let $\{X_{n,k} : k \leq h(n)\}$ be an enumeration of $W(\sigma)^2$ for $\sigma \in \Gamma_n$. Apply the previous proposition to see that almost surely

$$|\Gamma_n|^{-1} \sum_{\sigma \in \Gamma_n} W(\sigma)^2 \to c_2 \stackrel{def}{=} \mathbf{E} W^2 < \infty.$$

Now compute

$$\begin{aligned}
\sum_{|\sigma|=n} U(\sigma)^2 &= \left[\sum_{|\sigma|=n} W(\sigma) \right]^{-2} \sum_{|\sigma|=n} W(\sigma)^2 \\
&= m^{-2n} W(\Gamma)^{-2} |\Gamma_n| \left(|\Gamma_n|^{-1} \sum_{|\sigma|=n} W(\sigma)^2 \right) \\
&\leq m^{-n} W(\Gamma)^{-2} A_\Gamma \left(c_2 + \epsilon_n \right)
\end{aligned}$$

where $\epsilon_n \to 0$ as $n \to \infty$; this proves the lemma. $\square$

3 Mapping a tree to Euclidean space preserves capacity

In this section we extend a result of Benjamini and Peres (1992) showing how to map a tree into Euclidean space in a way that preserves capacity criteria. In order to interpret Theorem 1.1 in

Euclidean space, we employ the canonical mapping $\mathcal{R}$ from the boundary of a b^d-ary tree $\Gamma^{(b^d)}$ (every vertex has b^d children) to the cube $[0,1]^d$. Formally, label the edges from each vertex to its children in a one-to-one manner with the vectors in $\Omega = \{0, 1, \ldots, b-1\}^d$. Then the boundary $\partial\Gamma^{(b^d)}$ is identified with the sequence space $\Omega^{\mathbf{Z}^+}$ and we define $\mathcal{R} : \Omega^{\mathbf{Z}^+} \to [0,1]^d$ by

$$\mathcal{R}(\omega_1, \omega_2, \ldots) = \sum_{n=1}^{\infty} b^{-n} \omega_n. \tag{7}$$

Similarly, a vertex σ of $\Gamma^{(b^d)}$ is identified with a finite sequence $(\omega_1, \ldots, \omega_k) \in \Omega^k$ if $|\sigma| = k$, and we write $\mathcal{R}(\sigma)$ for the cube of side b^{-k} obtained as the image under $\mathcal{R}$ of all sequences in $\Omega^{\mathbf{Z}^+}$ with prefix $(\omega_1, \ldots, \omega_k)$.

The notions of energy and capacity are meaningful on any compact metric space. Given a decreasing function $g : (0, \infty) \to (0, \infty)$ such that $g(0+) = \infty$, define the energy of a Borel measure θ by

$$\overline{\mathcal{E}}(\theta) = \int \int g(|x-y|) \, d\theta(x) \, d\theta(y)$$

and the capacity of a set Λ by

$$\overline{\mathrm{Cap}}_g(\Lambda) = \left[\inf_{\theta(\Lambda)=1} \overline{\mathcal{E}}_g(\theta) \right]^{-1}.$$

(The bars come to distinguish this from the definition given for trees in Section 2.)

Theorem 3.1 *With the notation above, let T be a subtree of the b^d-ary tree $\Gamma^{(b^d)}$, so we may take $\partial T \subseteq \Omega^{\mathbf{Z}^+}$. Given a decreasing function $g : (0, \infty) \to (0, \infty)$ define $f(n) = g(b^{-n})$. Then for any finite measure θ on ∂T we have*

$$\mathcal{E}_f(\theta) < \infty \Leftrightarrow \overline{\mathcal{E}}_g(\theta \mathcal{R}^{-1}) < \infty \tag{8}$$

and in fact the ratio is bounded between positive constants depending only on the dimension d. It follows that

$$\mathrm{Cap}_f(T) > 0 \Leftrightarrow \overline{\mathrm{Cap}}_g(\mathcal{R}(\partial T)) > 0.$$

Remark 6: For $g(t) = \log(1/t)$ and $f(n) = n \log b$ this is proved in Benjamini and Peres (1992). As noted there, the potentials may become infinite when passing from the tree to Euclidean space.

PROOF: Let $h(k) = f(k) - f(k-1)$, where by convention $f(-1) = 0$. By (4),

$$\mathcal{E}_f(\theta) = \sum_{k=0}^{\infty} h(k) \sum_{|\sigma|=k} \theta(\sigma)^2 = \sum_{k=0}^{\infty} h(k) S_k \tag{9}$$

where $S_k = S_k(\theta) = \sum_{|\sigma|=k} \theta(\sigma)^2$. Now we wish to adapt this calculation to the set $\mathcal{R}(\partial T)$ in the cube $[0,1]^d$. First observe that the same argument yields

$$\begin{aligned} \overline{\mathcal{E}}_g(\theta\mathcal{R}^{-1}) &\leq \sum_{n=0}^{\infty} g(b^{-n})(\theta\mathcal{R}^{-1} \times \theta\mathcal{R}^{-1}) \left\{(x,y) : b^{-n} < |x-y| \leq b^{1-n}\right\} \\ &= \sum_{k=0}^{\infty} h(k)(\theta\mathcal{R}^{-1} \times \theta\mathcal{R}^{-1}) \left\{(x,y) : |x-y| \leq b^{1-k}\right\} , \end{aligned} \tag{10}$$

where we have implicitly assumed that θ has no atoms (otherwise the energies are automatically infinite).

For vertices σ, τ of T we write $\sigma \sim \tau$ if $\mathcal{R}(\sigma)$ and $\mathcal{R}(\tau)$ intersect (this is not an equivalence relation!). If $x, y \in \mathcal{R}(\partial T)$ satisfy $|x-y| \leq b^{1-k}$ then there exist vertices σ, τ of T with $|\sigma| = |\tau| = k-1$ and $\sigma \sim \tau$ satisfying $x \in \mathcal{R}(\sigma)$ and $y \in \mathcal{R}(\tau)$. Therefore

$$(\theta\mathcal{R}^{-1} \times \theta\mathcal{R}^{-1}) \left\{(x,y) : |x-y| \leq b^{1-k}\right\} \leq \sum_{|\sigma|=|\tau|=k-1} \mathbf{1}_{\{\sigma\sim\tau\}} \theta(\sigma)\theta(\tau).$$

Now use the inequality

$$\theta(\sigma)\theta(\tau) \leq \frac{\theta(\sigma)^2 + \theta(\tau)^2}{2}$$

and the key observation that

$$\#\{\tau \in T : |\tau| = |\sigma| \text{ and } \tau \sim \sigma\} \leq 3^d \quad \text{for all } \sigma \in T$$

to conclude that

$$(\theta\mathcal{R}^{-1} \times \theta\mathcal{R}^{-1}) \left\{(x,y) : |x-y| \leq b^{1-k}\right\} \leq 3^d S_{k-1}. \tag{11}$$

It is easy to compare S_{k-1} to S_k: clearly $|\sigma| = k-1$ implies that

$$\theta(\sigma)^2 = \left(\sum_{\tau \geq \sigma \, ; \, |\tau| = k} \theta(\tau) \right)^2 \leq b^d \sum_{\tau \geq \sigma \, ; \, |\tau| = k} \theta(\tau)^2$$

and therefore

$$S_{k-1} \leq b^d S_k. \tag{12}$$

Combining this with (10) and (11) yields

$$\overline{\mathcal{E}}_g(\theta \mathcal{R}^{-1}) \leq (3b)^d \sum_{k=0}^{\infty} h(k) S_k = (3b)^d \mathcal{E}_f(\theta).$$

This proves the direction ($\Rightarrow$) in (8).

The other direction is immediate in dimension $d = 1$ and easy in general:

$$\begin{aligned}
\overline{\mathcal{E}}_g(\theta \mathcal{R}^{-1}) &\geq \sum_{k=0}^{\infty} g(b^{-k}) (\theta \mathcal{R}^{-1} \times \theta \mathcal{R}^{-1}) \left\{ (x, y) : b^{-k-1} < |x - y| \leq b^{-k} \right\} \\
&= \sum_{n=0}^{\infty} h(n) (\theta \mathcal{R}^{-1} \times \theta \mathcal{R}^{-1}) \left\{ (x, y) : |x - y| \leq b^{-n} \right\} \\
&\geq \sum_{n=0}^{\infty} h(n) S_{n+l},
\end{aligned}$$

where l is chosen to satisfy $b^l \geq d^{1/2}$ and therefore

$$\left\{ (x, y) : |x - y| \leq b^{-n} \right\} \supseteq \bigcup_{|\sigma| = n+l} [\mathcal{R}(\sigma) \times \mathcal{R}(\sigma)].$$

Invoking (12) we get

$$\overline{\mathcal{E}}_g(\theta \mathcal{R}^{-1}) \geq b^{-dl} \sum_{n=0}^{\infty} h(n) S_n = b^{-dl} \mathcal{E}_f(\theta)$$

which completes the proof of (8).

The capacity assertion of the theorem follows, since any measure ν on $\mathcal{R}(\partial T) \subseteq [0, 1]^d$ can be written as $\theta \mathcal{R}^{-1}$ for an appropriate measure θ on ∂T. $\square$

4 Capacity-equivalence for Galton-Watson trees

In this section we prove the following weaker version of Theorem 1.1:

Theorem 4.1 *Let q be an offspring distribution with mean m and finite variance. Assume $q_0 = 0$. Then $\mathbf{P}_q$-almost every Γ has the property that for every increasing gauge function f,*

$$\mathrm{Cap}_f(\Gamma) > 0 \textit{ if and only if } \sum_{n=1}^{\infty} m^{-n} f(n) < \infty. \tag{13}$$

Remark 7: Graf, Mauldin and Williams (1988) show that the gauge functions for which such trees have positive Hausdorff measure differ depending on whether or not q is degenerate. Somehow this distinction vanishes when Hausdorff measure is replaced by capacity.

Remark 8: If m is an integer, then the RHS of (13) is finite if and only if the m-ary tree has positive capacity in gauge f (see Lyons 1992); if m is not an integer, then the same holds with a virtual m-ary tree as in Pemantle and Peres (1994b).

In order to interpret Theorem 4.1 probabilistically, and to see why it is indeed weaker than Theorem 1.1, we quote a fundamental theorem of R. Lyons (1992);

Theorem 4.2 (Lyons) *Suppose that for all $n \geq 1$ each edge connecting levels $n-1$ and n in a tree Γ is (independently of all other edges) erased with probability $1 - p_n$ and kept with probability p_n. Let $f(n)$ denote $\prod_{i=1}^{n} p_i^{-1}$. Then*

$$\frac{1}{2}\mathrm{Cap}_f(\Gamma) \leq \mathbf{P}(\textit{a ray of } \Gamma \textit{ survives}) \leq \mathrm{Cap}_f(\Gamma). \tag{14}$$

Remark 9: An alternative proof of this, which we now indicate, is given by Benjamini, Pemantle and Peres (1994). Think of Γ embedded in the plane, and consider the vertex–valued process obtained by jumping, left to right, on the n'*th* level vertices of Γ which are in the percolation cluster of the root. The key observation is that this is a Markov chain, so an appropriate general capacity estimate for hitting probabilities of Markov chains implies Theorem 4.2.

Remark 10: To put Theorem 4.2 in the framework of Section 1, consider IID variables $\{X(\sigma) : \sigma \in \Gamma\}$ uniform on $[0,1]$, and let B denote the Cartesian product set $\prod_{n=1}^{\infty}[0,p_n]$. Then $P(\Gamma; B)$, defined in Section 1, is precisely the probability that a ray of Γ survives the percolation.

PROOF OF THEOREM 4.1: One half of (13) is true without the finite variance assumption. Summing by parts, the RHS of (13) is equivalent to

$$\sum_{n=1}^{\infty} m^{-n}[f(n) - f(n-1)] < \infty. \tag{15}$$

Using (4) to express $\mathcal{E}_f$ and using the Cauchy-Schwarz inequality in the second line, we see that any unit flow θ satisfies

$$\begin{aligned}
\mathcal{E}_f(\theta) &= \sum_{n=1}^{\infty}[f(n) - f(n-1)] \sum_{|\sigma|=n} \theta(\sigma)^2 \\
&\geq \sum_{n=1}^{\infty}[f(n) - f(n-1)]|\Gamma_n|^{-1} \\
&\geq \sum_{n=1}^{\infty}[f(n) - f(n-1)]A_\Gamma^{-1} m^{-n},
\end{aligned}$$

where A_Γ is defined in equation (6). In particular, if the the sum in (15) is infinite, then any unit flow has infinite $\mathcal{E}_f$-energy and thus $\mathrm{Cap}_f(\Gamma) = 0$.

For the other direction, note that $\mathrm{Cap}_f(\Gamma) \geq \mathcal{E}_f(\theta)^{-1}$ for any unit flow θ. Pick $\theta = U$ and use Lemma 2.2 to get

$$\begin{aligned}
\mathcal{E}_f(U) &= \sum_{n=1}^{\infty}(f(n) - f(n-1)) \sum_{|\sigma|=n} U(\sigma)^2 \\
&\leq C_U \sum_{n=1}^{\infty}(f(n) - f(n-1)) m^{-n},
\end{aligned}$$

finishing the proof of (13) and the theorem. □

Hawkes (1981) determined the Hausdorff dimension of the boundary of a supercritical Galton-Watson tree and applied this to obtain the dimension of certain random sets in Euclidean space. Let $b \geq 2$ be an integer and let $\{q_k : 0 \leq k \leq b^d\}$ be a probability vector. Construct a random set $\Lambda \subseteq [0,1]^d$ as follows. By cutting $[0,1]$ into b intervals of length $1/b$ on each axis, we partition the unit cube into b^d congruent subcubes with disjoint interiors. We erase some of them, keeping k (closed) subcubes with probability q_k, the locations of the kept cubes being arbitrary. We iterate this procedure on each of the kept subcubes, keeping k sub-subcubes of each with probability q_k independently of everything else but arbitrarily located; continuing ad infinitum and intersecting the closed sets from each finite iteration yields the set Λ. Recalling the representation map $\mathcal{R} : \Omega^{\mathbf{Z}^+} \to [0,1]^d$ defined in (7) in the previous section, we can characterize the random set Λ as the image under $\mathcal{R}$ of the boundary of a Galton-Watson tree with offspring distribution $\{q_k\}$ that has been emebedded arbitrarily in the b^d-ary tree Γ. Hawkes showed that conditioned on non-extinction, Λ almost surely has Hausdorff dimension $\log_b(m)$. In terms of capacity, this says that for gauges $g(t) = t^{-\alpha}$, the supremum of α for which $\overline{\mathrm{Cap}}_g(\Lambda) > 0$ is $\log_b(m)$.

Combining Theorems 4.1 and 3.1 yields the following refinement.

Corollary 4.3 *Fix an integer $b > 1$ and let q be an offspring distribution with mean m such that $q_i = 0$ for all $i > b^d$. Then for $\mathbf{P}_q$-almost every T, the set $\Lambda = \mathcal{R}[\partial T] \subseteq [0,1]^d$ has the property that for all gauge functions g,*

$$\overline{\mathrm{Cap}}_g(\Lambda) > 0 \textit{ if and only if } \sum_{n=1}^{\infty} m^{-n} g(b^{-n}) < \infty. \tag{16}$$

□

5 Proof of Theorem 1.1

The proof relies on the construction of a product of the tree Γ with a tree of labels, and on the connection between $P(\Gamma; B)$ and a certain capacity in this product tree. These are outlined in

Lyons (1992) but only in the case where the distribution F of the random variables $X(\sigma)$ has finite support. The alternatives are to copy Lyons' development for arbitrary F or to reduce the proof of Theorem 1.1 to the case where F has finite support. We choose the latter alternative, since the reduction is not too long and capacity statements are clearer in the reduced case. This allows the reader the option of taking the reduction on faith and skipping the proof of Lemma 5.1. It is convenient at the same time to reduce to the case of finite trees.

Lemma 5.1 *Let Γ and Γ' be two infinite trees and suppose that there is a positive constant c_1 such that whenever N is finite, $B \subseteq \mathbb{R}^N$ and the common distribution F of the $X(\sigma)$ is uniform on a finite set $\{0, \ldots, b-1\}$, the inequality*

$$P(\Gamma'[N]; B; F) \leq c_1 P(\Gamma[N]; B; F) \tag{17}$$

holds, where $\Gamma[N]$ is the tree of height N agreeing with Γ up to level N. Then (17) holds for any closed set B, for any distribution F of the $X(\sigma)$, and with $N = \infty$.

Proof: It is easy to see that (17) for finite N and all B implies (17) for $N = \infty$ and all B: indeed, if $\pi_N(B)$ is the projection of B onto the first N coordinates then the fact that B is closed in the product topology implies that

$$P(\Gamma; B; F) = \lim_{N \to \infty} P(\Gamma; \pi_N^{-1}(\pi_N(B); F) = \lim_{N \to \infty} P(\Gamma[N]; \pi_N(B); F).$$

Thus, replacing B by $\pi_N(B)$ it suffices to show that for fixed trees Γ and Γ' of a fixed height N, the inequality (17) when F is supported on $\{0, \ldots, b-1\}$ implies (17) for any F. This will be accomplished by finitely approximating (F, B).

We may assume without loss of generality that the $X(\sigma)$ are uniform on the unit interval, since any distribution F may be obtained as the image of the uniform $[0,1]$ measure by some function f, and $P(\Gamma; B; F) = P(\Gamma; f^{-1}[B]; U[0,1])$. Fix a tree Γ of height N and a set $B \subseteq [0,1]^N$ and let U denote the distribution uniform on the unit interval. Let $\{X(\sigma)\}$ be IID random variables indexed by the vertices of Γ and having common distribution U. Let F_j denote the uniform distribution on $\{0, 1, \ldots, 2^j - 1\}$. Let $Y_j(\sigma) = \lfloor 2^j X(\sigma) \rfloor$; then $\{Y_j(\sigma)\}$ are

IID with common distribution F_j. Define discrete approximations $B^{(j)} \subseteq \{0, 1, \ldots, 2^j - 1\}^\infty$, depending only on the first n coordinates, by letting $(y_1, y_2, \ldots) \in B^{(j)}$ if and only if

$$\mathbf{P}\left[(X_1, \ldots, X_n) \in \pi_n(B) \mid \lfloor 2^j X_1 \rfloor = y_1, \ldots, \lfloor 2^j X_n \rfloor = y_n\right] > \frac{1}{2},$$

where X_i are IID with common distribution U.

Lemma 5.2 *Suppose the events $A(\Gamma; B^{(j)}; Y)$ and $A(\Gamma; B; X)$ are constructed on the same probability space as above. Then $A(\Gamma; B; X)$ is the almost sure limit of the events $A(\Gamma; B^{(j)}; Y)$.*

Proof: The event $A(\Gamma; B^{(j)}; Y\ )$ is the same as the event that $(Y(\sigma_1), \ldots, Y(\sigma_N)) \in B^{(j)}$ for some maximal path $(\rho, \sigma_1, \ldots, \sigma_N)$. Similarly, $A(\Gamma; B; X)$ is the event that $(X(\sigma_1), \ldots, X(\sigma_N)) \in B$ for some maximal path $(\rho, \sigma_1, \ldots, \sigma_N)$. Let $\mathcal{F}_j$ be the σ-field generated by the values of $\lfloor 2^j X(\sigma) \rfloor$ as σ ranges over vertices of Γ. For $\tau \in \Gamma_N$, let $(\sigma_1(\tau), \ldots, \sigma_N(\tau))$ denote the path from the root to τ, i.e., $\sigma_k(\tau)$ is the unique $\sigma \in \Gamma_k$ with $\sigma \leq \tau$. For any $\tau \in \Gamma_N$, the martingale convergence theorem shows that the event

$$\{(X(\sigma_1(\tau)), \ldots, X(\sigma_N(\tau))) \in B\}$$

is the almost sure limit of the events

$$\{\mathbf{P}[(X(\sigma_1(\tau)), \ldots, X(\sigma_N(\tau))) \in B \,|\, \mathcal{F}_j] > 1/2\}.$$

By construction, these are the events

$$\{(Y(\sigma_1(\tau)), \ldots, Y(\sigma_N(\tau))) \in B^{(j)}\}.$$

Taking the finite union over $\tau \in \Gamma_N$ proves the lemma. $\square$

The proof of Lemma 5.1 is now easily finished. Applying Lemma 5.2 to Γ and Γ', we see that

$$P(\Gamma; B; U) = \lim_{j \to \infty} P(\Gamma; B^{(j)}; F_j)$$

and similarly for Γ'. By assumption,

$$P(\Gamma'; B^{(j)}; F_j) \leq c_1 P(\Gamma; B^{(j)}; F_j).$$

Sending j to infinity finishes the proof of the lemma. $\square$

The continuation of the proof of Theorem 1.1 requires the following construction of a *product tree*, which is the analogue of a space-time Markov chain in the context of tree-indexed processes. For any $b \geq 2$ and $N < \infty$, let $\mathbf{b}^N$ be the b-ary tree of height N whose vertices are words of length at most N on the alphabet $\{0, \ldots, b-1\}$, with edges between each word and its b extensions by a single letter. If Γ and T are trees of the same height, let $\Gamma \times T$ denote the tree whose vertices are the pairs

$$\{(\sigma, x) : \sigma \in \Gamma, x \in T, |\sigma| = |x|\}$$

with $(\sigma, x) \leq (\tau, y)$ if and only if $\sigma \leq \tau$ and $x \leq y$. The utility of the product tree is in the following theorem due to R. Lyons (1992, Theorem 3.1); The proof of Theorem 4.2 given in Benjamini, Pemantle and Peres (1994) may be adapted in order to reduce the constant in (18) from 4 to 2, but since 4 is good enough for the sequel, we omit the adaptation.

Theorem 5.3 (Lyons) *Let F be the uniform distribution on $\{0, 1, \ldots, b-1\}$, let $N \geq 1$ and let $B \subseteq \{0, 1, \ldots b-1\}^N$. Let Γ be a tree of height N and define a kernel K on the boundary of $\Gamma \times \mathbf{b}^N$ by*

$$K((\alpha, x), (\beta, y)) = b^{|\alpha \wedge \beta|} \mathbf{1}_{\{|x \wedge y| \geq |\alpha \wedge \beta|\}}.$$

If $E = \partial\Gamma \times B \subseteq \partial(\Gamma \times \mathbf{b}^N)$ denotes the set $\{(\alpha, x) : \alpha \in \partial\Gamma \,, \, x \in B\}$, then

$$\mathrm{Cap}_K(E) \leq P(\Gamma; B) \leq 4\mathrm{Cap}_K(E). \tag{18}$$

$\square$

The theorem just stated is powerful, yet somewhat unwieldy to use, as it involves the product tree. Lyons (1992) showed that when Γ is a spherically symmetric tree (i.e., every vertex at level n has the same number of children), the capacity in (18) can be written as the capacity of the target set $\mathcal{B}$ in a certain gauge, thus recovering a theorem of Evans (1992). The next lemma gives less stringent regularity conditions on the tree Γ which allow a similar simplification.

Lemma 5.4 *Suppose that Γ is a tree of height N, and its edges are labelled by IID random variables. Assume that the label distribution F is uniform on $\{0,1,\ldots,b-1\}$, and that B is a subset of $\partial\mathbf{b}^N$ (or, equivalently, of $\{0,1,\ldots,b-1\}^N$). Let $\{M_j\}_{j=0}^N$ be a nondecreasing sequence of reals with $M_0=1$, and define the gauge function*

$$\phi(n)=\sum_{j=0}^{n} b^j\left(M_j^{-1}-M_{j+1}^{-1}\mathbf{1}_{\{j<N\}}\right). \tag{19}$$

(i) If

$$|\Gamma_n|\le A_\Gamma M_n \quad \text{for all } n\le N, \tag{20}$$

then

$$P(\Gamma;B)\le 8A_\Gamma \mathrm{Cap}_\phi(B). \tag{21}$$

(ii) If there is a unit flow U on Γ satisfying

$$\sum_{\sigma\in\Gamma_n} U(\sigma)^2\le C_U M_n^{-1} \quad \text{for all } n\le N. \tag{22}$$

then

$$C_U^{-1}\mathrm{Cap}_\phi(B)\le P(\Gamma;B). \tag{23}$$

(Roughly speaking, the coefficients C_U and A_Γ measure the discrepancy between the flow U on Γ and the uniform flow on a (possibly virtual) spherically–symmetric tree with level cardinalities $M_1,\ldots,M_N$.) Note that Fact 2.1 follows by applying part (i) of the lemma to a regular tree, and part (ii) to the given tree Γ.

PROOF OF LEMMA 5.4:
$(i\,)$ This relies on a comparison result from Pemantle and Peres (1994a). The essence of the argument may be stated simply: $P(\Gamma;B)$ can only increase if Γ is replaced by a symmetric tree of the same growth rate; for such a symmetric tree, $\mathrm{Cap}_\phi(B)$ essentially computes $P(\Gamma;B)$. Proceeding to the actual proof, we call a tree *spherically symmetric* if for each n,every vertex at level n has the same number of children. The necessary comparison result is:

Lemma 5.5 (Pemantle and Peres (1994a), Theorem 1) *Let Γ and T be two trees of height $N \leq \infty$ such that T is spherically symmetric and*

$$|\Gamma_n| \leq |T_n| \quad \textit{for all } n \leq N.$$

Then

$$P(\Gamma; B; F) \leq P(T; B; F)$$

for any closed set $B \subseteq \mathbb{R}^N$ and any distribution F.

$\Box$ Given a tree Γ which satisfies (20), consider a spherically symmetric tree T with generation sizes $|T_n|$ defined inductively by letting $|T_n|$ be the least integral multiple of $|T_{n-1}|$ satisfying $|T_n| \geq A_\Gamma M_n$. Clearly $|T_n| \leq 2A_\Gamma M_n$ for all n. Now use Theorem 5.3 to bound $P(\Gamma; B)$ from above. Since T is spherically symmetric, the capacity appearing in that lemma simplifies to

$$cap_K(\partial T \times B) = cap_\psi(B) \tag{24}$$

where

$$\psi(n) = \sum_{j=0}^{n} b^j \left(|T_j|^{-1} - |T_{j+1}|^{-1} \mathbf{1}_{\{j<N\}} \right)$$

(c.f. Lyons (1992, Corollary 3.2 and equation (3.8)).

Summing by parts, we compare energies in gauges ψ and ϕ:

$$\begin{aligned}
\mathcal{E}_\psi(\theta) &= \sum_{j=0}^{N} b^j \left(|T_j|^{-1} - |T_{j+1}|^{-1} \mathbf{1}_{\{j<N\}} \right) S_j(\theta) \\
&= \sum_{k=0}^{N} |T_k|^{-1} \left[b^k S_k(\theta) - b^{k-1} S_{k-1}(\theta) \mathbf{1}_{\{k>0\}} \right] \\
&\geq \frac{1}{2A_\Gamma} \sum_{k=0}^{N} M_k^{-1} \left[b^k S_k(\theta) - b^{k-1} S_{k-1}(\theta) \mathbf{1}_{\{k>0\}} \right] \\
&= \frac{1}{2A_\Gamma} \sum_{j=0}^{N} b^j S_j(\theta) \left(M_j^{-1} - M_{j+1}^{-1} \mathbf{1}_{\{j<N\}} \right)
\end{aligned}$$

$$= \frac{1}{2A_\Gamma}\mathcal{E}_\phi(\theta).$$

From the definition of capacity, it now follows that

$$\mathrm{Cap}_\psi(B) \le 2A_\Gamma \mathrm{Cap}_\phi(B)\,;$$

in conjunction with Theorem 5.3 and equation (24), this yields

$$P(T;B) \le 8A_\Gamma \mathrm{Cap}_\psi(B)\,,$$

and the comparison lemma 5.5 completes the proof of (21).

Proof of Lemma 5.4(ii): Given a unit flow θ on $\mathbf{b}^N$, let $U\times\theta$ be the flow on $\Gamma\times\mathbf{b}^N$ defined by

$$(U\times\theta)(\sigma,x) = U(\sigma)\theta(x).$$

For $k \le N$ define L^2 measurements of the flows U and θ by

$$S_k(U) = \sum_{\sigma\in\Gamma_k} U(\sigma)^2 \quad \text{and} \quad S_k(\theta) = \sum_{z\in\mathbf{b}^N_k} \theta(z)^2.$$

From Theorem 5.3,

$$\begin{aligned}
P(\Gamma;B)^{-1} &\le \mathrm{Cap}_K(\partial\Gamma\times B)^{-1} \\
&\le \mathcal{E}_K(U\times\theta) \\
&= \int\int_{\partial(\Gamma\times\mathbf{b}^N)} b^{|\alpha\wedge\beta|}\mathbf{1}_{\{|x\wedge y|\ge|\alpha\wedge\beta|\}}\, d(U\times\theta)(\alpha,x)\, d(U\times\theta)(\beta,y) \\
&= \sum_{x,y\in\partial\mathbf{b}^N} \theta(x)\theta(y) \sum_{i=0}^{|x\wedge y|} b^i (U\times U)\left\{(\alpha,\beta)\in\Gamma_N\times\Gamma_N\,:\,|\alpha\wedge\beta| = i\right\}. \\
&= \sum_{x,y\in\partial\mathbf{b}^N} \theta(x)\theta(y) \sum_{i=0}^{|x\wedge y|} b^i (S_i(U) - S_{i+1}(U)), \qquad (25)
\end{aligned}$$

where $S_{N+1}(U) = 0$ by convention. In order to apply the hypothesis (22) successfully, we must sum by parts to isolate S_i in (25) and then re-sum by parts. Accordingly,

$$\sum_{x,y\in\partial\mathbf{b}^N} \theta(x)\theta(y) \sum_{i=0}^{|x\wedge y|} b^i (S_i(U) - S_{i+1}(U))$$

$$= \sum_{k=0}^{N} S_k(U) \left[\sum_{|x\wedge y|\geq k} \theta(x)\theta(y) b^k - \mathbf{1}_{\{k>0\}} \sum_{|x\wedge y|\geq k-1} \theta(x)\theta(y) b^{k-1} \right]$$

$$= \sum_{k=0}^{N} S_k(U) \left[S_k(\theta) b^k - \mathbf{1}_{\{k>0\}} S_{k-1}(\theta) b^{k-1} \right] .$$

Using (22) together with the nonnegativity of $b^k S_k(U) - b^{k-1} S_{k-1}(U)$ (see (12)), we find that this is at most

$$\sum_{k=0}^{N} C_U M_k^{-1} \left[S_k(\theta) b^k - \mathbf{1}_{\{k>0\}} S_{k-1}(\theta) b^{k-1} \right]$$

$$= C_U \sum_{x,y\in\partial\mathbf{b}^N} \theta(x)\theta(y) \sum_{i=0}^{|x\wedge y|} b^i (M_j^{-1} - M_{j+1}^{-1} \mathbf{1}_{\{j<N\}})$$

$$= C_U \mathcal{E}_\phi(\theta).$$

Thus $P(\Gamma; B) \geq C_U^{-1} \mathcal{E}_\phi(\theta)^{-1}$ for any unit flow θ supported on B, which proves (23). $\square$

Proof of Theorem 1.1: The theorem follows readily from Lemma 5.4 with $M_n = m^n$ for all n: If Γ and Γ' are picked from Galton-Watson distributions $\mathbf{P}_q$ and $\mathbf{P}_{q'}$ of mean m and finite variance, then the finiteness of A_Γ and $A_{\Gamma'}$ is given in (6) and the limit-uniform flows U and U' on Γ and Γ' satisfy (22) by Lemma 2.2. Thus (21) and (23) imply that

$$\frac{P(\Gamma'; B)}{P(\Gamma; B)} \leq 8 A_{\Gamma'} C_U$$

for $B \subseteq \{0, 1, \ldots, b-1\}^N$; appealing to Lemma 5.1 completes the proof. $\square$

To justify Remark 5 (after the statement of Theorem 1.1), we point out that part (i) of Lemma 5.4 does not require finite offspring variance (using only the growth estimate (20) which, with $M_n = m^n$, holds a.s. for any Galton Watson tree with mean offspring m.) This shows that Galton-Watson trees with infinite offspring variance have at least as many polar sets as their finite-variance counterparts.

6 Branching processes in varying environments

A branching process in a varying environment (BPVE) is defined by a sequence of offspring generating functions

$$Q_n(s) = \sum_{k=0}^{\infty} q_n(k) s^k$$

where for each n, the nonnegative real numbers $\{q_n(k)\}$ sum to 1. From the sequence $\{Q_n\}$ a random tree Γ is constructed as follows. The root has a random number Z_1 of children, where $\mathbf{P}(Z_1 = k) = q_1(k)$. Each of these first-generation individuals has a random number of children, these random numbers $X_1, \ldots, X_{Z_1}$ being IID given Z_1 and satisfying $\mathbf{P}(X_1 = k) = q_2(k)$. This continues in the same manner, so that if Z_n is the number of individuals in generation n, then each of these Z_n individuals has (independently of all the others) k children with probability $q_{n+1}(k)$. We shall assume below that $q_n(0) = 0$ for all n.

Theorem 6.1 *Let $\{Q_n\}$ be a sequence of offspring generating functions satisfying $Q_n(0) = 0$, and let $\mathbf{P}_Q$ denote the law of the BPVE $\{Z_n\}$. Let $M_n = \prod_{j=1}^{n} Q_n'(1)$ be the $\mathbf{P}_Q$-expectation of Z_n. Let Δ be any infinite tree and denote the size of its n^{th} generation by $|\Delta_n|$. Assume that*

(i) $a := \inf_n Q_n'(1) > 1$;
(ii) $V := \sup_n Q_n''(1) < \infty$;
(iii) $A_\Delta := \sup_n |\Delta_n| / M_n < \infty$.

Then $\mathbf{P}_Q$-almost every tree Γ dominates Δ in the sense that there exists a finite constant C_1, depending only on the trees Γ and Δ, such that for every label distribution F and any closed set B in $I\!R^\infty$,

$$P(\Gamma; B; F) \geq C_1 P(\Delta; B; F).$$

Remark: In particular, two BPVE's satisfying (i) and (ii), with mean generation sizes differing by a bounded multiplicative factor, will generate equipolar trees almost surely.

First we state and prove an extension of Lemma 2.2 valid for BPVE's, and then we derive Theorem 6.1.

Lemma 6.2 *Let $\{Q_n\}$ and $\{M_n\}$ be as in Theorem 6.1. Then for $\mathbf{P}_Q$-almost every Γ there exist a probability measure $\overline{\theta}$ on the boundary of Γ and a constant C, such that for every n*

$$\sum_{\sigma\in\Gamma_n} \overline{\theta}(\sigma)^2 \leq C M_n^{-1}. \tag{26}$$

PROOF: For each vertex $\sigma \in \Gamma$ and $n \geq |\sigma|$, let $Z_n(\sigma)$ be the number of descendants of σ in generation n and $W_n(\sigma) = M_{|\sigma|} Z_n(\sigma)/M_n$. (We write Z_n for $Z_n(\rho)$.) For a fixed vertex σ, the sequence $\{W_n(\sigma)\}$ is a positive martingale with mean 1. It converges almost surely and in L^2 to a limit $W(\sigma)$ whose variance is easily estimated:

$$\begin{aligned}
Var(W(\sigma)) &= \sum_{j=|\sigma|}^{\infty} \mathbf{E}[\mathbf{E}(W_{j+1}(\sigma)^2 - W_j(\sigma)^2 | Z_j)] \\
&= \sum_{j=|\sigma|}^{\infty} \mathbf{E}[Z_j(Q''_{j+1}(1) + Q'_{j+1}(1) - Q'_{j+1}(1)^2)] M_{|\sigma|}^2 / M_{j+1}^2 \\
&\leq \sum_{j=|\sigma|}^{\infty} V M_j M_{|\sigma|} / M_{j+1}^2 \\
&\leq \frac{V}{a^2 - a}.
\end{aligned}$$

by assumption (ii). In particular, $D := \sup_\sigma \mathbf{E} W(\sigma)^2 < \infty$.

Define a flow U on Γ by

$$U(\sigma) = \frac{W(\sigma)}{M_{|\sigma|}} .$$

Let $S_k \subseteq \partial\Gamma$ be the set of rays $(\rho, v_1, v_2, \ldots)$ such that $W(v_n)^2 \leq M_n a^{-n/2}$ for each $n > k$. We will prove that almost surely, $U(S_k) > 0$ for all sufficiently large k, by showing that

$$\mathbf{E}U(\partial\Gamma \setminus \bigcap_k S_k) = 0\,.$$

Indeed, $\partial\Gamma \setminus S_k$ is equal to the union over $j > k$ of the sets of rays $(\rho, v_1, v_2, \ldots)$ for which $W(v_j)^2 > M_j a^{-j/2}$. Therefore $\mathbf{E}U(\partial\Gamma \setminus S_k)$ is at most

$$\sum_{j>k} M_j^{-1} \mathbf{E} Z_j \mathbf{E}(W(v_j) \mathbf{1}_{\{W(v_j)^2 > M_j a^{-j/2}\}})$$

where v_j is any vertex in generation j. Since $\mathbf{E}W(v_j)^2 \leq D$, it follows that

$$\mathbf{E}W(v_j)\mathbf{1}_{\{W(v_j)>L\}} \leq D/L$$

and thus that

$$\mathbf{E}U(\partial\Gamma \setminus S_k) \leq \frac{D}{M_k a^{-k/2}(1 - a^{-1/2})}.$$

This tends to zero as $k \to \infty$, proving the claim.

We now require an elementary large-deviation estimate which is easier to derive than to extract from the general theory:
For independent non-negative variables $\{X_i\}$, bounded by some constant b_1, whose means are bounded by b_2, convexity of the exponential implies that
$\mathbf{E}e^{X_i/b_1} \leq 1 + (e-1)b_2/b_1 \leq \exp((e-1)b_2/b_1)$ *, and therefore*

$$\mathbf{P}\left(\frac{1}{N}\sum_{i=1}^{N} X_i > 2b_2\right) \leq \mathbf{E}\exp\left(\sum_{i=1}^{N}\frac{X_i}{b_1} - 2N\frac{b_2}{b_1}\right) \leq \exp(-\frac{N}{b_1}(3-e)b_2). \tag{27}$$

Let $S := S_k$ for the least k such that $U(S_k) > 0$, and let θ be the restriction of U to S. Conditional on the level size $Z_n = Z_n(\rho)$, the values of $\theta(\sigma)^2$ for $|\sigma| = n$ are independent random variables, bounded pointwise by $M_n^{-1}a^{-n/2}$ (provided $n > k$), with means bounded by D/M_n^2. Thus by (27), for all $n > k$:

$$\mathbf{P}\left(\frac{1}{Z_n}\sum_{|\sigma|=n}\theta(\sigma)^2 > 2D/M_n^2 \,\Big|\, Z_n\right) \leq \exp(-Z_n M_n a^{n/2}(3-e)D/M_n^2).$$

Since $Z_n/M_n \to W(\rho) > 0$ a.s., this shows that these conditional probabilities are summable, and the conditional version of the Borel-Cantelli lemma (Assmussen and Hering (1983), p. 430) implies that the event on the left-hand-side of the last inequality can occur for at most finitely many n. Applying the a.s. convergence of Z_n/M_n to $W(\rho)$ again, we conclude that

$$\sum_{|\sigma|=n} \theta(\sigma)^2 < 4DM_n^{-1}W(\rho)$$

for all but finitely many n. This shows that the normalization $\overline{\theta}$ of θ to a probability measure satisfies (26), and proves the lemma. □

Proof of Theorem 6.1: By Lemma 5.1, it suffices to prove the theorem when the labelling distribution F is uniform on $\{0, \ldots, b-1\}$ and the target set B depends only on the first N coordinates. Recall the gauge function ϕ defined in Lemma 5.4. By part (i) of that lemma, $P(\Delta; B; F) \leq 8A_\Delta \mathrm{Cap}_\phi(B)$. By part (ii) of that lemma and Lemma 6.2, for $\mathbf{P}_Q$–almost every tree Γ there is a constant $C = C(\Gamma)$ such that $\mathrm{Cap}_\phi(B) \leq CP(\Gamma; B; F)$. Combining the last two inequalities completes the proof. □

7 Concluding remarks and questions

Aldous (1993, Theorem 23) has a (very different) invariance principle for *critical* Galton-Watson trees with finite offspring variance. This suggests that there might be stronger notions of equivalence between Galton-Watson trees yet to be exposed.

Finally, we list two unsolved problems which arise naturally from the results proved above.

(1) Does capacity-equivalence of two trees imply that they are equipolar? (Recall that the converse is contained in Theorem 4.2.) Even the special case in which one of the two capacity-equivalent trees is a regular tree or a Galton-Watson tree is not resolved; in that case, equipolarity would follow from an affirmative answer to the next question.

(2) Suppose a tree T is capacity-equivalent to Galton-Watson trees of mean m and finite variance. Does this imply that there exists a measure θ on ∂T such that

$$\sup_n m^n \sum_{|\sigma|=n} \theta(\sigma)^2 < \infty \ ?$$

References

[1] Aldous, D. (1993). The continuum random tree III. *Ann. Probab.* **21**, 248 - 289.

[2] Agresti, A. (1975). On the extinction times of varying and random environment branching processes. *J. Appl. Prob.* **12**, 39 - 46.

[3] Asmussen, S. and Hering, H. (1983). Branching processes. Birkhäuser: Boston.

[4] Athreya, K. and Ney, P. (1972). Branching Process. Springer-Verlag: New York.

[5] Barlow, M., Pemantle, R. and Perkins, E. (1993). A stringy-tree growth model. *Preprint.*

[6] Benjamini, I., Pemantle, R. and Peres, Y. (1994). Martin capacity for Markov chains. *Preprint.*

[7] Benjamini, I. and Peres, Y. (1992). Random walks on a tree and capacity in the interval. *Annals Inst. H. Poincare* **28**, 557 - 592.

[8] Benjamini, I. and Peres, Y. (1994a). Tree-indexed random walks on groups and first passage percolation. *Prob. Th. and Rel. Fields* **98**, 91 - 112.

[9] Benjamini, I. and Peres, Y. (1994b). Markov chains indexed by trees. *Ann. Probab.* **22**, 219 - 243

[10] Bramson, M. (1978). Minimal displacement of branching random walk. *Zeit. Wahr.* **45**, 89 - 108.

[11] Derrida, B. and Spohn, H. (1988). Polymers on disordered trees, spin glasses, and traveling waves. *J. Stat. Phys.* **51**, 817 - 841.

[12] Dubins, L. and Freedman, D. (1967). Random distribution functions. Proceedings of the fifth Berkeley Symposium on mathematical statistics and probability (LeCam and Neyman, Eds.): University of California Press.

[13] Evans, S. (1992). Polar and non-polar sets for a tree-indexed process. *Ann. Probab.* **20**, 579 - 590.

[14] Graf, S., Mauldin, R. D. and Williams, S. C. (1988). The exact Hausdorff dimension in random recursive constructions. American Mathematical Society: Providence.

[15] Hawkes, J. (1981). Trees generated by a simple branching process. *J. London Math. Soc.* **24**, 373 - 384.

[16] Kesten, H. (1978). Branching Brownian motion with absorption. *Stoch. Proc. Appl.* **47**, 9 - 47.

[17] Lyons, R. (1992). Random walks, capacity and percolation on trees. *Ann. Probab.* **20**, 2043 - 2088.

[18] Lyons, R. and Pemantle, R. (1992). Random walk in random environment and first-passage percolation on trees. *Ann. Probab.* **20**, 125 - 136.

[19] Lyons, R., Pemantle, R. and Peres, Y. (1994). Ergodic theory on Galton-Watson trees: Speed of random walk and dimension of harmonic measure. *Erg. Th. and Dyn. Sys. to appear.*

[20] Pemantle, R. (1992). Critical random walk in random environment on trees of exponential growth. In: *Proc. Sem. Stoch. Proc. 1992*, Burdzy and Bass, Editors.

[21] Pemantle, R. (1994). Sharpness of second moment criteria for branching and tree-indexed processes. *Preprint.*

[22] Pemantle, R. and Peres, Y. (1994a). Domination between trees and application to an explosion problem. *Ann. Probab.* **22**, 180 - 194.

[23] Pemantle, R. and Peres, Y. (1994b). Critical Random walk in random environment on trees. *Ann. Probab. to appear.*

[24] Sawyer, S. (1978). Isotropic random walks in a tree. *Zeit. Wahrsch.* **42**, 279 - 292.

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