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# LOCAL LIMITS OF GALTON-WATSON TREES CONDITIONED ON THE NUMBER OF PROTECTED NODES

ROMAIN ABRAHAM, AYMEN BOUAZIZ, AND JEAN-FRANÇOIS DELMAS

ABSTRACT. We consider a marking procedure of the vertices of a tree where each vertex is marked independently from the others with a probability that depends only on its out-degree. We prove that a critical Galton-Watson tree conditioned on having a large number of marked vertices converges in distribution to the associated size-biased tree. We then apply this result to give the limit in distribution of a critical Galton-Watson tree conditioned on having a large number of protected nodes.

## 1. INTRODUCTION

In [6], Kesten proved that a critical or sub-critical Galton-Watson (GW) tree conditioned on reaching at least height  $h$  converges in distribution (for the local topology on trees) as  $h$  goes to infinity toward the so-called sized-biased tree (that we call here Kesten's tree and whose distribution is described in Section 3.2). Since then, other conditionings have been considered, see [1, 2, 4] and the references therein for recent developments on the subject.

A protected node is a node that is not a leaf and none of its offsprings is a leaf. Precise asymptotics for the number of protected nodes in a conditioned GW tree have already been obtained in [3, 5] for instance. Let  $A(\mathbf{t})$  be the number of protected nodes in the tree  $\mathbf{t}$ . Remark that this functional  $A$  is clearly monotone in the sense of [4] (using for instance (13)); therefore, using Theorem 2.1 of [4], we immediately get that a critical GW tree  $\tau$  conditioned on  $\{A(\tau) > n\}$  converges in distribution toward Kesten's tree as  $n$  goes to infinity. Conditioning on  $\{A(\tau) = n\}$  needs extra work and is the main objective of this paper. Using the general result of [1], if we have the following limit

$$(1) \quad \lim_{n \rightarrow +\infty} \frac{\mathbb{P}(A(\tau) = n + 1)}{\mathbb{P}(A(\tau) = n)} = 1,$$

then the critical GW tree  $\tau$  conditioned on  $\{A(\tau) = n\}$  converges in distribution also toward Kesten's tree, see Theorem 5.1.

In fact, the limit (1) can be seen as a special case of a more general problem: conditionally given the tree, we mark the nodes of the tree independently of the rest of the tree with a probability that depends only on the number of offsprings of the nodes. Then we prove that a critical GW tree conditioned on the total number of marked nodes being large converges in distribution toward Kesten's tree, see Theorem 3.3.

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The paper is then organized as follows: we first recall briefly the framework of discrete trees, then we consider in Section 3 the problem of a marked GW tree and the proofs of the results are given in Section 4. In particular, we prove the limit (1) when  $A$  is the number of marked nodes in Lemma 4.2 and we deduce the convergence of a critical GW tree conditioned on the number of marked nodes toward Kesten's tree in Theorem 3.3. We finally explain in Section 5 how the problem of protected nodes can be viewed as a problem on marked nodes and deduce the convergence in distribution of a critical GW tree conditioned on the number of protected nodes toward Kesten's tree in Theorem 5.1.

## 2. TECHNICAL BACKGROUND ON GW TREES

### 2.1. The set of discrete trees.

We denote by  $\mathbb{N} = \{0, 1, 2, \dots\}$  the set of non-negative integers and by  $\mathbb{N}^* = \{1, 2, \dots\}$  the set of positive integers.

If  $E$  is a subset of  $\mathbb{N}^*$ , we call the span of  $E$  the greatest common divisor of  $E$ . If  $X$  is an integer-valued random variable, we call the span of  $X$  the span of  $\{n > 0; \mathbb{P}(X = n) > 0\}$ .

We recall Neveu's formalism [7] for ordered rooted trees. Let  $\mathcal{U} = \bigcup_{n \geq 0} (\mathbb{N}^*)^n$  be the set of finite sequences of positive integers with the convention  $(\mathbb{N}^*)^0 = \{\emptyset\}$ . For  $u \in \mathcal{U}$ , its length or generation  $|u| \in \mathbb{N}$  is defined by  $u \in (\mathbb{N}^*)^{|u|}$ . If  $u$  and  $v$  are two sequences of  $\mathcal{U}$ , we denote by  $uv$  the concatenation of the two sequences, with the convention that  $uv = u$  if  $v = \emptyset$  and  $uv = v$  if  $u = \emptyset$ . The set of ancestors of  $u$  is the set

$$\text{An}(u) = \{v \in \mathcal{U}; \exists w \in \mathcal{U} \text{ such that } u = vw\}.$$

Notice that  $u$  belongs to  $\text{An}(u)$ . For two distinct elements  $u$  and  $v$  of  $\mathcal{U}$ , we denote by  $u < v$  the lexicographic order on  $\mathcal{U}$  i.e.  $u < v$  if  $u \in \text{An}(v)$  and  $u \neq v$  or if  $u = wiu'$  and  $v = wjv'$  for some  $i, j \in \mathbb{N}^*$  with  $i < j$ . We write  $u \leq v$  if  $u = v$  or  $u < v$ .

A tree  $\mathbf{t}$  is a subset of  $\mathcal{U}$  that satisfies:

- $\emptyset \in \mathbf{t}$ .
- If  $u \in \mathbf{t}$ , then  $\text{An}(u) \subset \mathbf{t}$ .
- For every  $u \in \mathbf{t}$ , there exists  $k_u(\mathbf{t}) \in \mathbb{N}$  such that, for every  $i \in \mathbb{N}^*$ ,  $ui \in \mathbf{t}$  iff  $1 \leq i \leq k_u(\mathbf{t})$ .

The vertex  $\emptyset$  is called the root of  $\mathbf{t}$ . The integer  $k_u(\mathbf{t})$  represents the number of offsprings of the vertex  $u \in \mathbf{t}$ . The set of children of a vertex  $u \in \mathbf{t}$  is given by:

$$(2) \quad C_u(\mathbf{t}) = \{ui; 1 \leq i \leq k_u(\mathbf{t})\}.$$

By convention, we set  $k_u(\mathbf{t}) = -1$  if  $u \notin \mathbf{t}$ .

A vertex  $u \in \mathbf{t}$  is called a leaf if  $k_u(\mathbf{t}) = 0$ . We denote by  $\mathcal{L}_0(\mathbf{t})$  the set of leaves of  $\mathbf{t}$ . A vertex  $u \in \mathbf{t}$  is called a *protected node* if  $C_u(\mathbf{t}) \neq \emptyset$  and  $C_u(\mathbf{t}) \cap \mathcal{L}_0(\mathbf{t}) = \emptyset$ , that is  $u$  is not a leaf and none of its children is a leaf. For  $u \in \mathbf{t}$ , we define  $F_u(\mathbf{t})$ , the fringe subtree of  $\mathbf{t}$  above  $u$ , as

$$F_u(\mathbf{t}) = \{v \in \mathbf{t}; u \in \text{An}(v)\} = \{uv; v \in S_u(\mathbf{t})\}$$

with  $S_u(\mathbf{t}) = \{v \in \mathcal{U}; uv \in \mathbf{t}\}$ .

Notice that  $S_u(\mathbf{t})$  is a tree. We denote by  $\mathbb{T}$  the set of trees and by  $\mathbb{T}_0 = \{\mathbf{t} \in \mathbb{T}; \text{Card}(\mathbf{t}) < +\infty\}$  the subset of finite trees.

We say that a sequence of trees  $(\mathbf{t}_n, n \in \mathbb{N})$  converges locally to a tree  $\mathbf{t}$  if and only if  $\lim_{n \rightarrow \infty} k_u(\mathbf{t}_n) = k_u(\mathbf{t})$  for all  $u \in \mathcal{U}$ . Let  $(T_n, n \in \mathbb{N})$  and  $T$  be  $\mathbb{T}$ -valued random variables. We denote by  $\text{dist}(T)$  the distribution of the random variable  $T$  and write

$$\lim_{n \rightarrow +\infty} \text{dist}(T_n) = \text{dist}(T)$$

for the convergence in distribution of the sequence  $(T_n, n \in \mathbb{N})$  to  $T$  with respect to the local topology.

If  $\mathbf{t}, \mathbf{t}' \in \mathbb{T}$  and  $x \in \mathcal{L}_0(\mathbf{t})$  we denote by

$$(3) \quad \mathbf{t} \otimes_x \mathbf{t}' = \{u \in \mathbf{t}\} \cup \{xv; v \in \mathbf{t}'\}$$

the tree obtained by grafting the tree  $\mathbf{t}'$  on the leaf  $x$  of the tree  $\mathbf{t}$ . For every  $\mathbf{t} \in \mathbb{T}$  and every  $x \in \mathcal{L}_0(\mathbf{t})$ , we shall consider the set of trees obtained by grafting a tree on the leaf  $x$  of  $\mathbf{t}$ :

$$\mathbb{T}(\mathbf{t}, x) = \{\mathbf{t} \otimes_x \mathbf{t}'; \mathbf{t}' \in \mathbb{T}\}.$$

**2.2. Galton Watson trees.** Let  $p = (p(n), n \in \mathbb{N})$  be a probability distribution on  $\mathbb{N}$ . We assume that

$$(4) \quad p(0) > 0, p(0) + p(1) < 1, \text{ and } \mu := \sum_{n=0}^{+\infty} np(n) < +\infty.$$

A  $\mathbb{T}$ -valued random variable  $\tau$  is a GW tree with offspring distribution  $p$  if the distribution of  $k_\emptyset(\tau)$  is  $p$  and it enjoys the branching property: for  $n \in \mathbb{N}^*$ , conditionally on  $\{k_\emptyset(\tau) = n\}$ , the subtrees  $(F_1(\tau), \dots, F_n(\tau))$  are independent and distributed as the original tree  $\tau$ .

The GW tree and the offspring distribution are called critical (resp. sub-critical, super-critical) if  $\mu = 1$  (resp.  $\mu < 1$ ,  $\mu > 1$ ).

### 3. CONDITIONING ON THE NUMBER OF MARKED VERTICES

**3.1. Definition of the marking procedure.** We begin with a fixed tree  $\mathbf{t}$ . We add marks on the vertices of  $\mathbf{t}$  in an independent way such that the probability of adding a mark on a node  $u$  depends only on the number of children of  $u$ . More precisely, we consider a mark function  $q : \mathbb{N} \rightarrow [0, 1]$  and a family of independent Bernoulli random variables  $(Z_u(\mathbf{t}), u \in \mathbf{t})$  such that for all  $u \in \mathbf{t}$ :

$$\mathbb{P}(Z_u(\mathbf{t}) = 1) = 1 - \mathbb{P}(Z_u(\mathbf{t}) = 0) = q(k_u(\mathbf{t})).$$

The vertex  $u$  is said to have a mark if  $Z_u(\mathbf{t}) = 1$ . We denote by  $\mathcal{M}(\mathbf{t}) = \{u \in \mathbf{t}; Z_u(\mathbf{t}) = 1\}$  the set of marked vertices and by  $M(\mathbf{t})$  its cardinal. We call  $(\mathbf{t}, \mathcal{M}(\mathbf{t}))$  a marked tree.

A marked GW tree with offspring distribution  $p$  and mark function  $q$  is a couple  $(\tau, \mathcal{M}(\tau))$ , with  $\tau$  a GW tree with offspring distribution  $p$  and conditionally on  $\{\tau = \mathbf{t}\}$  the set of marked vertices  $\mathcal{M}(\tau)$  is distributed as  $\mathcal{M}(\mathbf{t})$ .

*Remark 3.1.* Notice that for  $\mathcal{A} \subseteq \mathbb{N}$ , if we set  $q(k) = \mathbf{1}_{\{k \in \mathcal{A}\}}$ , then the set  $\mathcal{M}(\mathbf{t})$  is just the set of vertices with out-degree (i.e. number of offsprings) in  $\mathcal{A}$  considered in [1, 8]. Hence, the above construction can be seen as an extension of this case.

**3.2. Kesten's tree.** Let  $p$  be an offspring distribution satisfying Assumption (4) with  $\mu \leq 1$  (i.e. the associated GW process is critical or sub-critical). We denote by  $p^* = (p^*(n) = np(n)/\mu, n \in \mathbb{N})$  the corresponding size-biased distribution.

We define an infinite random tree  $\tau^*$  (the size-biased tree that we call Kesten's tree in this paper) whose distribution is described as follows:

There exists a unique infinite sequence  $(v_k, k \in \mathbb{N}^*)$  of positive integers such that, for every  $h \in \mathbb{N}$ ,  $v_1 \cdots v_h \in \tau^*$ , with the convention that  $v_1 \cdots v_h = \emptyset$  if  $h = 0$ . The joint distribution of  $(v_k, k \in \mathbb{N}^*)$  and  $\tau^*$  is determined recursively as follows. For each  $h \in \mathbb{N}$ , conditionally given  $(v_1, \dots, v_h)$  and  $\{u \in \tau^*; |u| \leq h\}$  the tree  $\tau^*$  up to level  $h$ , we have:

- The number of children  $(k_u(\tau^*), u \in \tau^*, |u| = h)$  are independent and distributed according to  $p$  if  $u \neq v_1 \cdots v_h$  and according to  $p^*$  if  $u = v_1 \cdots v_h$ .
- Given  $\{u \in \tau^*; |u| \leq h + 1\}$  and  $(v_1, \dots, v_h)$ , the integer  $v_{h+1}$  is uniformly distributed on the set of integers  $\{1, \dots, k_{v_1 \cdots v_h}(\tau^*)\}$ .

*Remark 3.2.*

Notice that by construction, a.s.  $\tau^*$  has a unique infinite spine. And following Kesten [6], the random tree  $\tau^*$  can be viewed as the tree  $\tau$  conditioned on non extinction.

For  $\mathbf{t} \in \mathbb{T}_0$  and  $x \in \mathcal{L}_0(\mathbf{t})$ , we have:

$$\mathbb{P}(\tau^* \in \mathbb{T}(t, x)) = \frac{\mathbb{P}(\tau = t)}{\mu^{|x|} p(0)}.$$

### 3.3. Main theorem.

**Theorem 3.3.** *Let  $p$  be a critical offspring distribution that satisfies Assumption (4). Let  $(\tau, \mathcal{M}(\tau))$  be a marked GW tree with offspring distribution  $p$  and mark function  $q$  such that  $p(k)q(k) > 0$  for some  $k \in \mathbb{N}$ . For every  $n \in \mathbb{N}^*$ , let  $\tau_n$  be a tree whose distribution is the conditional distribution of  $\tau$  given  $\{M(\tau) = n\}$ . Let  $\tau^*$  be a Kesten's tree associated with  $p$ . Then we have:*

$$\lim_{n \rightarrow +\infty} \text{dist}(\tau_n) = \text{dist}(\tau^*),$$

where the limit has to be understood along a subsequence for which  $\mathbb{P}(M(\tau) = n) > 0$ .

*Remark 3.4.* If for every  $k \in \mathbb{N}$ ,  $0 < q(k) < 1$ , then  $\mathbb{P}(M(\tau) = n) > 0$  for every  $n \in \mathbb{N}$ , hence the above conditioning is always valid.

## 4. PROOF OF THEOREM 3.3

Set  $\gamma = \mathbb{P}(M(\tau) > 0)$ . Since there exists  $k \in \mathbb{N}$  with  $p(k)q(k) > 0$ , we have  $\gamma > 0$ . A sufficient condition (but not necessary) to have  $\mathbb{P}(M(\tau) = n) > 0$  for every  $n$  large enough is to assume that  $\gamma < 1$  (see Lemma 4.3 and Section 4.4). Taking  $q = \mathbf{1}_{\mathcal{A}}$ , see Remark 3.1 for  $0 \in \mathcal{A} \subset \mathbb{N}$  implies  $\gamma = 1$  and some periodicity may occur.

The following result is the analogue in the random case of Theorem 3.1 in [1] and its proof is in fact a straightforward adaptation of the proof in [1] by using:

- (i)  $M(\mathbf{t}) \leq \text{Card}(\mathbf{t})$ .
- (ii) For every  $\mathbf{t} \in \mathbb{T}_0$ ,  $x \in \mathcal{L}_0(\mathbf{t})$  and  $\mathbf{t}' \in \mathbb{T}$ , we have that  $M(\mathbf{t} \otimes_x \mathbf{t}')$  is distributed as  $\hat{M}(\mathbf{t}') + M(\mathbf{t}) - \mathbf{1}_{\{Z_x(\mathbf{t})=1\}}$ , where  $\hat{M}(\mathbf{t}')$  is distributed as  $M(\mathbf{t}')$  and is independent of  $\mathcal{M}(\mathbf{t})$ .

**Proposition 4.1.** *Let  $n_0 \in \mathbb{N} \cup \{\infty\}$ . Assume that  $\mathbb{P}(M(\tau) \in [n, n + n_0]) > 0$  for  $n$  large enough. Then, if*

$$(5) \quad \lim_{n \rightarrow +\infty} \frac{\mathbb{P}(M(\tau) \in [n + 1, n + 1 + n_0])}{\mathbb{P}(M(\tau) \in [n, n + n_0])} = 1,$$

we have:

$$\lim_{n \rightarrow +\infty} \text{dist}(\tau | M(\tau) \in [n, n + n_0]) = \text{dist}(\tau^*).$$

*Proof.* According to Lemma 2.1 in [1], a sequence  $(T_n, n \in \mathbb{N})$  of finite random trees converges in distribution (with respect to the local topology) to some Kesten's tree  $\tau^*$  if and only if, for every finite tree  $\mathbf{t} \in \mathbb{T}_0$  and every leaf  $x \in \mathcal{L}_0(\mathbf{t})$ ,

$$(6) \quad \lim_{n \rightarrow +\infty} \mathbb{P}((T_n \in \mathbb{T}(\mathbf{t}, x)) = \mathbb{P}(\tau^* \in \mathbb{T}(\mathbf{t}, x)) \quad \text{and} \quad \lim_{n \rightarrow +\infty} \mathbb{P}(T_n = \mathbf{t}) = 0.$$

Let  $\mathbf{t} \in \mathbb{T}_0$  and  $x \in \mathcal{L}_0(\mathbf{t})$ . We set  $D(\mathbf{t}, x) = M(\mathbf{t}) - \mathbf{1}_{\{Z_x(\mathbf{t})=1\}}$ . Notice that  $D(\mathbf{t}, x) \leq \text{Card}(\mathbf{t}) - 1$ . Elementary computations give for every  $\mathbf{t}' \in \mathbb{T}_0$  that:

$$\mathbb{P}(\tau = \mathbf{t} \otimes \mathbf{t}') = \frac{1}{p(0)} \mathbb{P}(\tau = \mathbf{t}) \mathbb{P}(\tau = \mathbf{t}') \quad \text{and} \quad \mathbb{P}(\tau^* \in \mathbb{T}(\mathbf{t}, x)) = \frac{1}{p(0)} \mathbb{P}(\tau = \mathbf{t}).$$

As  $\tau$  is a.s. finite, we have:

$$\begin{aligned} & \mathbb{P}(\tau \in \mathbb{T}(\mathbf{t}, x), M(\tau) \in [n, n + n_0]) \\ &= \sum_{\mathbf{t}' \in \mathbb{T}_0} \mathbb{P}(\tau = \mathbf{t} \otimes_x \mathbf{t}', M(\tau) \in [n, n + n_0]) \\ &= \sum_{\mathbf{t}' \in \mathbb{T}_0} \mathbb{P}(\tau = \mathbf{t} \otimes_x \mathbf{t}') \mathbb{P}(M(\mathbf{t} \otimes_x \mathbf{t}') \in [n, n + n_0]) \\ &= \sum_{\mathbf{t}' \in \mathbb{T}_0} \frac{\mathbb{P}(\tau = \mathbf{t}) \mathbb{P}(\tau = \mathbf{t}')}{p(0)} \mathbb{P}(\hat{M}(\mathbf{t}') + D(\mathbf{t}, x) \in [n, n + n_0]) \\ &= \mathbb{P}(\tau^* \in \mathbb{T}(\mathbf{t}, x)) \mathbb{P}(\hat{M}(\tau) + D(\mathbf{t}, x) \in [n, n + n_0]). \end{aligned}$$

Notice that:

$$\begin{aligned} & \mathbb{P}(\hat{M}(\tau) + D(\mathbf{t}, x) \in [n, n + n_0]) \\ &= \sum_{k=0}^{\text{Card}(\mathbf{t})-1} \mathbb{P}(\hat{M}(\tau) + D(\mathbf{t}, x) \in [n, n + n_0] \mid D(\mathbf{t}, x) = k) \mathbb{P}(D(\mathbf{t}, x) = k) \\ &= \sum_{k=0}^{\text{Card}(\mathbf{t})-1} \mathbb{P}(M(\tau) \in [n - k, n + n_0 - k]) \mathbb{P}(D(\mathbf{t}, x) = k). \end{aligned}$$

Then we obtain using Assumption (5) that:

$$\lim_{n \rightarrow +\infty} \frac{\mathbb{P}(\hat{M}(\tau) + D(\mathbf{t}, x) \in [n, n + n_0])}{\mathbb{P}(M(\tau) \in [n, n + n_0])} = 1,$$

that is

$$\lim_{n \rightarrow +\infty} \mathbb{P}(\tau \in \mathbb{T}(\mathbf{t}, x) \mid M(\tau) \in [n, n + n_0]) = \mathbb{P}(\tau^* \in \mathbb{T}(\mathbf{t}, x)).$$

This proves the first limit of (6).

The second limit is immediate since, for every  $n \geq \text{Card}(\mathbf{t})$ ,

$$\mathbb{P}(\tau = \mathbf{t} \mid M(\tau) \in [n, n + n_0]) = 0.$$

□

The main ingredient for the proof of Theorem 3.3 is then the following lemma.

**Lemma 4.2.** *Let  $d$  be the span of the random variable  $M(\tau) - 1$ . We have*

$$(7) \quad \lim_{n \rightarrow +\infty} \frac{\mathbb{P}(M(\tau) \in [n + 1, n + 1 + d])}{\mathbb{P}(M(\tau) \in [n, n + d])} = 1.$$

The end of this section is devoted to the proof of Lemma 4.2, see Section 4.4, which follows the ideas of the proof of Theorem 5.1 of [1].

**4.1. Transformation of a subset of a tree onto a tree.** We recall Rizzolo's map [8] which from  $\mathbf{t} \in \mathbb{T}_0$  and a non-empty subset  $A$  of  $\mathbf{t}$  builds a tree  $\mathbf{t}_A$  such that  $\text{Card}(A) = \text{Card}(\mathbf{t}_A)$ . We will give a recursive construction of this map  $\phi: (\mathbf{t}, A) \mapsto \mathbf{t}_A = \phi(\mathbf{t}, A)$ . We will check in the next section that this map is such that if  $\tau$  is a GW tree then  $\tau_A$  will also be a GW tree for a well chosen subset  $A$  of  $\tau$ . Figure 1 below shows an example of a tree  $\mathbf{t}$ , a set  $A$  and the associated tree  $\mathbf{t}_A$  which helps to understand the construction.

For a vertex  $u \in \mathbf{t}$ , recall  $C_u(\mathbf{t})$  is the set of children of  $u$  in  $\mathbf{t}$ . We define for  $u \in \mathbf{t}$ :

$$R_u(\mathbf{t}) = \bigcup_{w \in \text{An}(u)} \{v \in C_w(\mathbf{t}); u < v\}$$

the vertices of  $\mathbf{t}$  which are larger than  $u$  for the lexicographic order and are children of  $u$  or of one of its ancestors. For a vertex  $u \in \mathbf{t}$ , we shall consider  $A_u$  the set of elements of  $A$  in the fringe subtree above  $u$ :

$$(8) \quad A_u = A \cap F_u(\mathbf{t}) = A \cap \{uv; v \in S_u(\mathbf{t})\}.$$

Let  $\mathbf{t} \in \mathbb{T}_0$  and  $A \subset \mathbf{t}$  such that  $A \neq \emptyset$ . We shall define  $\mathbf{t}_A = \phi(\mathbf{t}, A)$  recursively. Let  $u_0$  be the smallest (for the lexicographic order) element of  $A$ . Consider the fringe subtrees of  $\mathbf{t}$  that are rooted at the vertices in  $R_{u_0}(\mathbf{t})$  and contain at least one vertex in  $A$ , that is  $(F_u(\mathbf{t}); u \in R_{u_0}^A(\mathbf{t}))$ , with

$$R_{u_0}^A(\mathbf{t}) = \{u \in R_{u_0}(\mathbf{t}); A_u \neq \emptyset\} = \{u \in R_{u_0}(\mathbf{t}); \exists v \in A \text{ such that } u \in \text{An}(v)\}.$$

Define the number of children of the root of tree  $\mathbf{t}_A$  as the number of those fringe subtrees:

$$k_\emptyset(\mathbf{t}_A) = \text{Card}(R_{u_0}^A(\mathbf{t})).$$

If  $k_\emptyset(\mathbf{t}_A) = 0$  set  $\mathbf{t}_A = \{\emptyset\}$ . Otherwise let  $u_1 < \dots < u_{k_\emptyset(\mathbf{t}_A)}$  be the ordered elements of  $R_{u_0}^A(\mathbf{t})$  with respect to the lexicographic order on  $\mathcal{U}$ . And we define  $\mathbf{t}_A = \phi(\mathbf{t}, A)$  recursively by:

$$(9) \quad F_i(\mathbf{t}_A) = \phi(F_{u_i}(\mathbf{t}), A_{u_i}) \quad \text{for } 1 \leq i \leq k_\emptyset(\mathbf{t}_A).$$

Since  $\text{Card}(A_{u_i}) < \text{Card}(A)$ , we deduce  $\mathbf{t}_A = \phi(\mathbf{t}, A)$  is well defined and it is a tree by construction. Furthermore, we clearly have that  $A$  and  $\mathbf{t}_A$  have the same cardinal:

$$(10) \quad \text{Card}(\mathbf{t}_A) = \text{Card}(A).$$

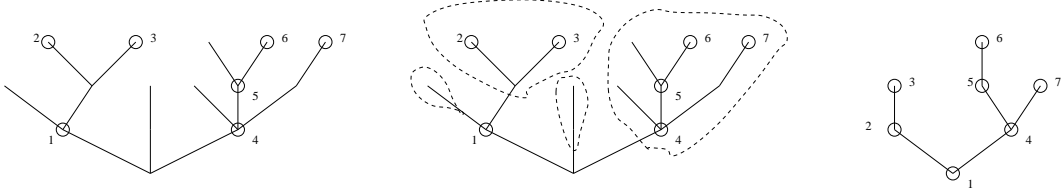


FIGURE 1. Left: A tree  $\mathbf{t}$  and the set  $A$ . Center: The fringe subtrees rooted at the vertices in  $R_{u_0}(\mathbf{t})$ . Left: the tree  $\mathbf{t}_A$ . The labels have no signification, they only show which node of  $\mathbf{t}$  corresponds to a node of  $\mathbf{t}_A$

**4.2. Distribution of the number of marked nodes.** Let  $(\tau, \mathcal{M}(\tau))$  be a marked GW tree with critical offspring distribution  $p$  satisfying (4) and mark function  $q$ . Recall  $\gamma = \mathbb{P}(M(\tau) > 0) = \mathbb{P}(\mathcal{M}(\tau) \neq \emptyset)$ .

Let  $((X_i, Z_i), i \in \mathbb{N}^*)$  be i.i.d. random variables such that  $X_i$  is distributed according to  $p$  and  $Z_i$  is conditionally on  $X_i$  Bernoulli with parameter  $q(X_i)$ . We define:

- $G = \inf\{k \in \mathbb{N}^*; \sum_{i=1}^k (X_i - 1) = -1\}$ .
- $N = \inf\{k \in \mathbb{N}^*; Z_k = 1\}$ .
- $\tilde{X}$  a random variable distributed as  $1 + \sum_{i=1}^N (X_i - 1)$  conditionally on  $\{N \leq G\}$ .
- $Y$  a random variable which is conditionally on  $\tilde{X}$  binomial with parameter  $(\tilde{X}, \gamma)$ .

We say that a probability distribution on  $\mathbb{N}$  is aperiodic if the span of its support restricted to  $\mathbb{N}^*$  is 1. The following result is immediate as the distribution  $p$  of  $X_1$  satisfies (4).

**Lemma 4.3.** *The distribution of  $Y$  satisfies (4) and if  $\gamma < 1$  then it is aperiodic.*

Recall that for a tree  $\mathbf{t} \in \mathbb{T}_0$ , we have:

$$(11) \quad \sum_{u \in \mathbf{t}} (k_u(\mathbf{t}) - 1) = -1$$

and  $\sum_{u \in \mathbf{t}, u < v} (k_u(\mathbf{t}) - 1) > -1$  for any  $v \in \mathbf{t}$ . We deduce that  $G$  is distributed according to  $\text{Card}(\tau)$  and thus  $N$  is distributed like the index of the first marked vertex along the depth-first walk of  $\tau$ . Then, we have:

$$(12) \quad \gamma = \mathbb{P}(N \leq G).$$



We denote by  $(\tau^0, \mathcal{M}(\tau^0))$  a random marked tree distributed as  $(\tau, \mathcal{M}(\tau))$  conditioned on  $\{\mathcal{M}(\tau) \neq \emptyset\}$ . By construction,  $\text{Card}(\tau^0)$  is distributed as  $G$  conditioned on  $\{N \leq G\}$ .

**Lemma 4.4.** *Under the hypothesis of this section, we have that  $\tau_{\mathcal{M}(\tau^0)}^0 = \phi(\tau^0, \mathcal{M}(\tau^0))$  is a critical GW tree with the law of  $Y$  as offspring distribution.*

**4.3. Proof of Lemma 4.4.** In order to simplify notation, we write  $\tilde{\tau}$  for  $\tau_{\mathcal{M}(\tau^0)}^0 = \phi(\tau^0, \mathcal{M}(\tau^0))$  and for  $u \in \tau^0$ , we set  $R_u$  for  $R_u(\tau^0)$ .

**Lemma 4.5.** *The random tree  $\tilde{\tau}$  is a GW tree with offspring distribution the law of  $Y$ .*

*Proof.* Let  $u_0$  be the smallest (for the lexicographic order) element of  $\mathcal{M}(\tau^0)$ . The branching property of GW trees implies that, conditionally given  $u_0$  and  $R_{u_0}$ , the fringe subtrees of  $\tau^0$  rooted at the vertices in  $R_{u_0}$ ,  $(S_u(\tau^0), u \in R_{u_0})$  are independent and distributed as  $\tau$ . Recall notation (8) so that the set of marked vertices of the fringe subtree rooted at  $u$  is  $\mathcal{M}_u(\tau^0) = \mathcal{M}(\tau^0) \cap F_u(\tau^0)$ . Define  $\tilde{\mathcal{M}}_u(\tau^0) = \{v; uv \in \mathcal{M}_u(\tau^0)\}$  the corresponding marked vertices of  $S_u(\mathbf{t})$ . Then, the construction of the marks  $\mathcal{M}(\tau)$  implies that the corresponding marked trees  $((S_u(\tau^0), \tilde{\mathcal{M}}_u(\tau^0)), u \in R_{u_0})$  are independent and distributed as  $(\tau, \mathcal{M}(\tau))$ . Notice that for  $u \in R_{u_0}$ , the fringe subtree  $F_u(\tau^0)$  contains at least one mark iff  $u$  belongs to

$$R_{u_0}^{\mathcal{M}(\tau^0)} = \{u \in R_{u_0}; \exists v \in \mathcal{M}(\tau^0) \text{ such that } u \in \text{An}(v)\}.$$

Then by considering only the fringe subtrees containing at least one mark, we get that, conditionally on  $R_{u_0}^{\mathcal{M}(\tau^0)}$ , the subtrees  $((S_u(\tau^0), \tilde{\mathcal{M}}_u(\tau^0)), u \in R_{u_0}^{\mathcal{M}(\tau^0)})$  are independent and distributed as  $(\tau^0, \mathcal{M}(\tau^0))$ . We deduce from the recursive construction of the map  $\phi$ , see (9), that  $\tilde{\tau}$  is a GW tree. Notice that the offspring distribution of  $\tilde{\tau}$  is given by the distribution of the cardinal of  $R_{u_0}^{\mathcal{M}(\tau^0)}$ . We now compute the corresponding offspring distribution. We first give an elementary formula for the cardinal of  $R_u(\mathbf{t})$ . Let  $\mathbf{t} \in \mathbb{T}_0$  and  $u \in \mathbf{t}$ . Consider the tree  $\mathbf{t}' = R_u(\mathbf{t}) \cup \{v \in \mathbf{t}; v \leq u\}$ . Using (11) for  $\mathbf{t}'$ , we get:

$$-1 = \sum_{v \in \mathbf{t}'} (k_v(\mathbf{t}') - 1) = \sum_{v \in \mathbf{t}; v \leq u} (k_v(\mathbf{t}') - 1) + \sum_{v \in R_u(\mathbf{t})} (-1).$$

This gives  $\text{Card}(R_u(\mathbf{t})) = 1 + \sum_{v \in \mathbf{t}; v \leq u} (k_v(\mathbf{t}') - 1)$ . We deduce from the definition of  $\tilde{X}$  that  $\text{Card}(R_{u_0})$  is distributed as  $\tilde{X}$ . We deduce from the first part of the proof that conditionally on  $\text{Card}(R_{u_0})$ , the distribution of  $\text{Card}(R_{u_0}^{\mathcal{M}(\tau^0)})$  is binomial with parameter  $(\text{Card}(R_{u_0}(\tau^0)), \gamma)$ . This gives that the offspring distribution of  $\tilde{\tau}$  is given by the law of  $Y$ .  $\square$

**Lemma 4.6.** *The GW tree  $\tilde{\tau}$  is critical.*

*Proof.* Since the offspring distribution is the law of  $Y$  we need to check that  $\mathbb{E}[Y] = 1$  that is  $\gamma \mathbb{E}[\tilde{X}] = 1$  since  $Y$  is conditionally on  $\tilde{X}$  binomial with parameter  $(\tilde{X}, \gamma)$ .

Recall  $N$  has finite expectation as  $\mathbb{P}(Z_1 = 1) > 0$ , is not independent of  $(X_i)_{i \in \mathbb{N}^*}$  and is a stopping time with respect to the filtration generated by  $((X_i, Z_i), i \in \mathbb{N}^*)$ .

Using Wald's equality and  $\mathbb{E}[X_i] = 1$ , we get  $\mathbb{E}\left[\sum_{i=1}^N (X_i - 1)\right] = 0$  and thus using the definition of  $\tilde{X}$  as well as (12):

$$\gamma\mathbb{E}[\tilde{X}] = \gamma + \mathbb{E}\left[\sum_{i=1}^N (X_i - 1)\mathbf{1}_{\{N \leq G\}}\right] = \gamma - \mathbb{E}\left[\sum_{i=1}^N (X_i - 1)\mathbf{1}_{\{N > G\}}\right].$$

We have:

$$\begin{aligned} \mathbb{E}\left[\sum_{i=1}^N (X_i - 1)\mathbf{1}_{\{N > G\}}\right] &= \mathbb{E}\left[\sum_{i=1}^G (X_i - 1)\mathbf{1}_{\{N > G\}}\right] + \mathbb{P}(N > G)\mathbb{E}\left[\sum_{i=1}^N (X_i - 1)\right] \\ &= -\mathbb{P}(N > G) \\ &= \gamma - 1, \end{aligned}$$

where we used the strong Markov property of  $((X_i, Z_i), i \in \mathbb{N}^*)$  at the stopping time  $G$  for the first equation, the definition of  $T$  and Wald's equality for the second, and (12) for the third. We deduce that  $\mathbb{E}[Y] = \gamma\mathbb{E}[\tilde{X}] = 1$ , which ends the proof.  $\square$

**4.4. Proof of (7).** According to Lemma 4.4 and (10), we have that  $M(\tau^0)$  is distributed as the total size of a critical GW whose offspring distribution satisfies (4). The proof of Proposition 4.3 of [1] (see Equation (4.15) in [1]) entails that if  $\tau'$  is a critical GW tree, then, if  $d$  denotes the span of the random variable  $\text{Card}(\tau') - 1$ , we have

$$\lim_{n \rightarrow \infty} \frac{\mathbb{P}(\text{Card}(\tau') \in [n+1, n+1+d])}{\mathbb{P}(\text{Card}(\tau') \in [n, n+d])} = 1.$$

## 5. PROTECTED NODES

Recall that a node of a tree  $\mathbf{t}$  is protected if it is not a leaf and none of its offsprings is a leaf. We denote by  $A(\mathbf{t})$  the number of protected nodes of the tree  $\mathbf{t}$ .

**Theorem 5.1.** *Let  $\tau$  be a critical GW tree with offspring distribution  $p$  satisfying (4) and let  $\tau^*$  be the associated Kesten's tree. Let  $\tau_n$  be a random tree distributed as  $\tau$  conditionally given  $\{A(\tau) = n\}$ . Then:*

$$\lim_{n \rightarrow +\infty} \text{dist}(\tau_n) = \text{dist}(\tau^*).$$

*Proof.* Notice that  $\mathbb{P}(A(\tau) = n) > 0$  for all  $n \in \mathbb{N}$ . Notice that the functional  $A$  satisfies the additive property of [1], namely for every  $\mathbf{t} \in \mathbb{T}$ , every  $x \in \mathcal{L}_0(\mathbf{t})$  and every  $\mathbf{t}' \in \mathbb{T}$  that is not reduced to the root, we have

$$(13) \quad A(\mathbf{t} \otimes_x \mathbf{t}') = A(\mathbf{t}) + A(\mathbf{t}') + D(\mathbf{t}, x)$$

where  $D(\mathbf{t}, x) = 1$  if  $x$  is the only child of its first ancestor which is a leaf (therefore this ancestor becomes a protected node in  $\mathbf{t} \otimes_x \mathbf{t}'$ ) and  $D(\mathbf{t}, x) = 0$  otherwise. According to Theorem 3.1 of [1], to end the proof it is enough to check that

$$(14) \quad \lim_{n \rightarrow +\infty} \frac{\mathbb{P}(A(\tau) = n+1)}{\mathbb{P}(A(\tau) = n)} = 1.$$

For a tree  $\mathbf{t} \neq \{\emptyset\}$ , let  $\mathbf{t}_{\mathbb{N}^*} = \phi(\mathbf{t}, \mathbf{t} \setminus \mathcal{L}_0(\mathbf{t}))$  be the tree obtained from  $\mathbf{t}$  by removing the leaves. Let  $\tau^0$  be a random tree distributed as  $\tau$  conditioned to  $\{k_\emptyset(\tau) > 0\}$ . Using Theorem 6 and Corollary 2 of [8] with  $A = \mathbb{N}^*$  (or Lemma 4.4 with  $q(k) = \mathbf{1}_{\{k>0\}}$ ), we have that  $\tau_{\mathbb{N}^*}^0$  is a critical GW tree with offspring distribution:

$$p_{\mathbb{N}^*}(k) = \sum_{n=\max(k,1)}^{+\infty} p(n) \binom{n}{k} (p(0))^{n-k} (1-p(0))^{k-1}, \quad k \in \mathbb{N}.$$

Conditionally given  $\{\tau_{\mathbb{N}^*}^0 = \mathbf{t}\}$ , we consider independent random variables  $(W(u), u \in \mathbf{t})$  taking values in  $\mathbb{N}^*$  whose distributions are given for all  $u \in \mathbf{t}$  by  $\mathbb{P}(W(u) = 0) = 0$  for  $k_u(\mathbf{t}) = 0$  and otherwise for  $k_u(\mathbf{t}) + n > 0$  (remark that  $p_{\mathbb{N}^*}(k_u(\mathbf{t})) > 0$ ), by

$$\mathbb{P}(W(u) = n) = \frac{p(k_u(\mathbf{t}) + n)}{p_{\mathbb{N}^*}(k_u(\mathbf{t}))} \binom{k_u(\mathbf{t}) + n}{n} p(0)^n (1-p(0))^{k_u(\mathbf{t})-1}.$$

In particular for  $k_u(\mathbf{t}) > 0$ , we have:

$$(15) \quad \mathbb{P}(W(u) = 0) = \frac{p(k_u(\mathbf{t}))}{p_{\mathbb{N}^*}(k_u(\mathbf{t}))} (1-p(0))^{k_u(\mathbf{t})-1}.$$

Then, we define a new tree  $\hat{\tau}$  by grafting, on every vertex  $u$  of  $\tau_{\mathbb{N}^*}^0$ ,  $W(u)$  leaves in a uniform manner, see Figure 2.

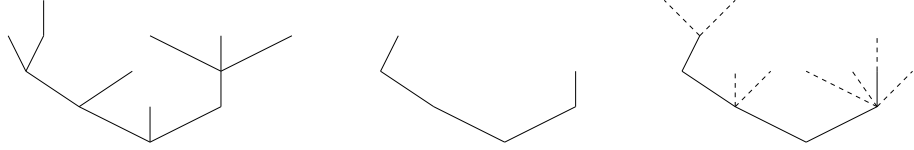


FIGURE 2. The trees  $\tau^0$ ,  $\tau_{\mathbb{N}^*}^0$  and  $\hat{\tau}$

More precisely, given  $\tau_{\mathbb{N}^*}^0$  and  $(W(u), u \in \tau_{\mathbb{N}^*}^0)$ , we define a tree  $\hat{\tau}$  and a random map  $\psi : \tau_{\mathbb{N}^*}^0 \mapsto \hat{\tau}$  recursively in the following way. We set  $\psi(\emptyset) = \emptyset$ . Then, given  $k_\emptyset(\tau_{\mathbb{N}^*}^0) = k$ , we set  $k_\emptyset(\hat{\tau}) = k + W(\emptyset)$ . We also consider a family  $(i_1, \dots, i_k)$  of integer-valued random variables such that  $(i_1, i_2 - i_1, \dots, i_k - i_{k-1}, W(u) + k + 1 - i_k)$  is a uniform positive partition of  $W(u) + k + 1$ . Then, for every  $j \leq k$  such that  $j \notin \{i_1, \dots, i_k\}$ , we set  $k_j(\hat{\tau}) = 0$  i.e. these are leaves of  $\hat{\tau}$ . For every  $1 \leq j \leq k$ , we set  $\psi(j) = i_j$  and we apply to them the same construction as for the root and so on.

**Lemma 5.2.** *The new tree  $\hat{\tau}$  is distributed as the original tree  $\tau^0$ .*

*Proof.* Let  $\mathbf{t} \in \mathbb{T}_0$ . As  $\mathbb{P}(\hat{\tau} = \{\emptyset\}) = 0$ , we assume that  $k_\emptyset(\mathbf{t}) > 0$ . Let  $\mathbf{t}_{\mathbb{N}^*}$  be the tree obtained from  $\mathbf{t}$  by removing the leaves. Using (11), we have:

$$\begin{aligned} \mathbb{P}(\hat{\tau} = \mathbf{t}) &= \prod_{u \in \mathbf{t}_{\mathbb{N}^*}} p_{\mathbb{N}^*}(k_u(\mathbf{t}_{\mathbb{N}^*})) \mathbb{P}(W(u) = k_u(\mathbf{t}) - k_u(\mathbf{t}_{\mathbb{N}^*})) \frac{1}{\binom{k_u(\mathbf{t})}{k_u(\mathbf{t}) - k_u(\mathbf{t}_{\mathbb{N}^*})}} \\ &= \frac{\mathbb{P}(\tau = \mathbf{t})}{1 - p(0)} \\ &= \mathbb{P}(\tau^0 = \mathbf{t}). \end{aligned}$$

□

Notice that the protected nodes of  $\hat{\tau}$  are exactly the nodes of  $\tau_{\mathbb{N}^*}^0$  on which we did not add leaves i.e. for which  $W(u) = 0$ . If we set  $\mathcal{M}(\tau_{\mathbb{N}^*}^0) = \{u \in \tau_{\mathbb{N}^*}^0, W(u) = 0\}$ , we have  $M(\tau_{\mathbb{N}^*}^0) = A(\hat{\tau})$ .

Using (15), we get that the corresponding mark function  $q$  is given by:

$$q(k) = \frac{p(k)(1-p(0))^{k-1}}{p_{\mathbb{N}^*}(k)} \mathbf{1}_{\{k \geq 1\}}.$$

As  $\hat{\tau}$  is distributed as  $\tau^0$ , we have:

$$\lim_{n \rightarrow +\infty} \frac{\mathbb{P}(A(\tau^0) = n+1)}{\mathbb{P}(A(\tau^0) = n)} = \lim_{n \rightarrow +\infty} \frac{\mathbb{P}(A(\hat{\tau}) = n+1)}{\mathbb{P}(A(\hat{\tau}) = n)} = \lim_{n \rightarrow +\infty} \frac{\mathbb{P}(M(\tau_{\mathbb{N}^*}^0) = n+1)}{\mathbb{P}(M(\tau_{\mathbb{N}^*}^0) = n)}.$$

As  $\tau_{\mathbb{N}^*}^0$  is a critical GW tree, we deduce from Lemma 4.2 that

$$\lim_{n \rightarrow +\infty} \frac{\mathbb{P}(M(\tau_{\mathbb{N}^*}^0) = n+1)}{\mathbb{P}(M(\tau_{\mathbb{N}^*}^0) = n)} = 1.$$

As  $\mathbb{P}(A(\tau) = n) = \mathbb{P}(A(\tau) = n | k_\emptyset(\tau) > 0) \mathbb{P}(k_\emptyset(\tau) > 0)$  and  $\mathbb{P}(A(\tau) = n | k_\emptyset(\tau) > 0) = \mathbb{P}(A(\tau^0) = n)$  for  $n \geq 2$ , we obtain (14) and hence end the proof. □

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