# Asymptotic Enumeration of Spanning Trees 

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#### Abstract

We give new general formulas for the asymptotics of the number of spanning trees of a large graph. A special case answers a question of McKay (1983) for regular graphs. The general answer involves a quantity for infinite graphs that we call "tree entropy", which we show is a logarithm of a normalized determinant of the graph Laplacian for infinite graphs. Tree entropy is also expressed using random walks. We relate tree entropy to the metric entropy of the uniform spanning forest process on quasi-transitive amenable graphs, extending a result of Burton and Pemantle (1993).


## §1. Introduction.

Methods of enumeration of spanning trees in a finite graph $G$ and relations to various areas of mathematics and physics have been investigated for more than 150 years. The number of spanning trees is often called the complexity of the graph, denoted here by $\tau(G)$. The best known formula for the complexity, proved in every basic text on graph theory, is called "the Matrix-Tree Theorem", which expresses it as a determinant. One is often interested in asymptotics of the complexity of a sequence of finite graphs that approach (in some sense) some infinite graph. Use of the Matrix-Tree Theorem typically involves calculating eigenvalues and their asymptotics. ${ }^{1}$ This often leads to a formula of the form

$$
\lim _{n \rightarrow \infty} \frac{1}{\left|\mathrm{~V}\left(G_{n}\right)\right|} \log \tau\left(G_{n}\right)=\int \log f
$$

[^0]for some function $f$ on the unit cube of some Euclidean space, where $\mathrm{V}\left(G_{n}\right)$ is the vertex set of $G_{n}$. One of the cases that is most well known, due to its connection with domino tilings, is that where the graphs $G_{n}$ approach the usual square lattice, i.e., the nearest-neighbor graph on $\mathbb{Z}^{2}$. In this case, one has that
$$
\lim _{n \rightarrow \infty}\left|\mathrm{~V}\left(G_{n}\right)\right|^{-1} \log \tau\left(G_{n}\right)=\int_{0}^{1} \int_{0}^{1} \log (4-2 \cos 2 \pi x-2 \cos 2 \pi y) d x d y=4 \mathrm{G} / \pi
$$
where $\mathrm{G}:=\sum_{k=0}^{\infty}(-1)^{k} /(2 k+1)^{2}=0.9160^{-}$is Catalan's constant. See, e.g., Burton and Pemantle (1993) and Shrock and Wu (2000) and the references therein for this and several other such examples. We shall reformulate the Matrix-Tree Theorem as an infinite series whose terms have a probabilistic meaning (see Proposition 3.1). In fact, the terms of the series are "local" quantities. This will permit us to find the asymptotic complexity in a very general setting (see Theorem 3.3). Other than assuming a bound on the average degree of the finite graphs of whose complexity we find the asymptotics, our results are essentially the most general possible. In the simplest case, where the finite graphs $G_{n}$ tend to a fixed transitive infinite graph $G$, we shall prove that
$$
\lim _{n \rightarrow \infty}\left|\mathrm{~V}\left(G_{n}\right)\right|^{-1} \log \tau\left(G_{n}\right)=\mathbf{h}(G):=\log \operatorname{deg}_{G}(o)-\sum_{k \geq 1} p_{k}(o ; G) / k
$$
where $o$ is a fixed vertex of $G$ and $p_{k}(o ; G)$ is the probability that simple random walk started at $o$ on $G$ is again at $o$ after $k$ steps. We term $\mathbf{h}(G)$ the tree entropy ${ }^{2}$ of $G$. We have chosen this terminology to reflect both its provenance as a limit of entropies per vertex of uniform spanning trees of finite graphs as well as its agreement (up to normalization) with the metric entropy of uniform spanning forests in certain infinite graphs (see Theorem 5.1), as we shall discuss shortly.

Our result allows us to find asymptotics that were not known previously. For a simple example, in case the graphs $G_{n}$ approach the regular tree of degree 4, then

$$
\lim _{n \rightarrow \infty}\left|\mathrm{~V}\left(G_{n}\right)\right|^{-1} \log \tau\left(G_{n}\right)=3 \log (3 / 2)
$$

see Example 3.16. This answers a question of McKay (1983), who had shown such a result only under stronger conditions on the sequence of graphs $G_{n}$, and who had noted (in the case of regular graphs) that, if sufficient, our conditions would be weakest possible.

In the past, it has been observed by direct calculation that one has the same asymptotic complexity both of rectangular portions of $\mathbb{Z}^{d}$ as well as of $d$-dimensional tori. Our

[^1]first main result, Theorem 3.3, shows that this stability phenomenon is quite general; see Corollary 3.13.

Our infinite series representation of the asymptotic complexity has an additional benefit. Namely, even when an integral representation is known, it turns out that for numerical estimation, our infinite series can be much better than the integral ${ }^{3}$; see, e.g., Felker and Lyons (2003) for examples comparing the two approaches.

In order to state our second main result, we recall the Matrix-Tree Theorem. Given a graph $G$, define the following matrices indexed by the vertices of $G$ : Let $D_{G}$ be the diagonal matrix whose $(x, x)$-entry equals the degree of $x$; this is the degree matrix. Let $A_{G}$ be the matrix whose $(x, y)$-entry equals the number of edges joining $x$ and $y$; this is the adjacency matrix. Finally, let $\Delta_{G}:=D_{G}-A_{G}$, the graph Laplacian matrix. The Matrix-Tree Theorem says that given any finite graph $G$, every cofactor of $\Delta_{G}$ is the same, namely, $\tau(G)$ (see, e.g., Godsil and Royle (2001), Lemma 13.2.3). Another version of the Matrix-Tree Theorem states that when $G$ is connected,

$$
\begin{equation*}
\tau(G)=|\mathrm{V}(G)|^{-1} \operatorname{det}^{\prime} \Delta_{G}, \tag{1.1}
\end{equation*}
$$

where $\operatorname{det}^{\prime} A$ denotes the product of the non-zero eigenvalues of a matrix $A$ (see, e.g., Godsil and Royle (2001), Lemma 13.2.4). Thus, the asymptotic complexity of a sequence of graphs is a limit of the logarithm of the determinant of the graph Laplacians, appropriately normalized. Our second main aim is to give meaning to and to prove the formula

$$
\mathbf{h}(G)=\log \operatorname{Det} \Delta_{G}
$$

directly in terms of a normalized determinant of the graph Laplacian for infinite graphs. We shall also use this formula to prove inequalities for tree entropy and to calculate easily and quickly the classical tree entropy for Euclidean lattices. Indeed, this result, Theorem 4.1, provides a quick way to derive virtually all the prior asymptotics of this type in the literature, while Theorem 3.3 gives the rest (and more).

We have alluded to the fact that tree entropy also arises as the entropy per vertex of a measure that is the weak limit of the uniform measures on spanning trees of finite graphs. To state this precisely, we must first recall the work of Pemantle (1991). He proved a conjecture of the present author, namely, that if an infinite connected graph $G$ is exhausted by a sequence of finite connected subgraphs $G_{n}$, then the weak limit of the uniform spanning tree measures on $G_{n}$ exists. However, it may happen that the limit

[^2]measure is not supported on trees, but on forests. This limit measure is now called the free uniform spanning forest on $G$, denoted FSF , or $\mathrm{FSF}_{G}$ when we want to indicate the graph $G$. If $G$ is itself a tree, then this measure is trivial, namely, it is concentrated on $\{G\}$. Therefore, Häggström (1998) introduced another limit that had been considered on $\mathbb{Z}^{d}$ more implicitly by Pemantle (1991) and explicitly by Häggström (1995), namely, the weak limit of the uniform spanning tree measures on $G_{n}^{*}$, where $G_{n}^{*}$ is the graph $G_{n}$ with its boundary identified to a single vertex. As Pemantle (1991) showed, this limit also always exists on any graph and is now called the wired uniform spanning forest, denoted WSF or $\mathrm{WSF}_{G}$. It is clear that both FSF and WSF are concentrated on the set of spanning forests ${ }^{4}$ of $G$ that are essential, meaning that all their trees are infinite. Furthermore, since the limits exist regardless of the exhaustion chosen, both $\mathrm{FSF}_{G}$ and $\mathrm{WSF}_{G}$ are invariant under any automorphisms that $G$ may have. As shown by Häggström (1995), $\mathrm{FSF}_{G}=\mathrm{WSF}_{G}$ on every amenable transitive graph $G$ such as $\mathbb{Z}^{d}$. In fact, the proof of this result given by Benjamini, Lyons, Peres, and Schramm (2001), hereinafter referred to as BLPS (2001), is easily modified to show that the same holds for every quasitransitive amenable graph, using the notion of natural frequency distribution recalled below in Section 5. Both FSF and WSF are important in their own right; see Lyons (1998) for a survey and BLPS 2001) for a comprehensive treatment.

Suppose now that $\Gamma$ is an amenable group that acts quasi-transitively on a graph $G$. Since $\mathrm{FSF}_{G}$ is defined as a limit of uniform measures, it is natural to expect that it has maximum (metric) entropy in an appropriate class of $\Gamma$-invariant measures. Since the set of essential spanning forests is closed, one generally considers the class of $\Gamma$-invariant measures on this set. Furthermore, one might expect that the entropy of $\mathrm{FSF}_{G}$ is related in a simple way to the exponential growth rate of the complexity of the finite subgraphs $G_{n}$ exhausting $G$. Finally, one might wonder whether $\mathrm{FSF}_{G}$ is unique as a measure of maximal entropy on the essential spanning forests.

The case of $\Gamma=\mathbb{Z}^{d}$ was considered by Burton and Pemantle (1993). Their Theorem 6.1 gave a positive answer to all three questions implicit in the preceding paragraph. However, it turns out that one of the claims, the uniqueness of the measure of maximal entropy, received an incorrect proof. The correct proofs of the other claims relied to some extent on the natural tiling of $\mathbb{Z}^{d}$ by large boxes, which is not available in general amenable quasi-transitive graphs. The third aim of this paper is to extend these two other claims to amenable quasi-transitive graphs, that is, to prove that the formula for entropy is correct and to prove that this entropy is maximal (see Theorem 5.1). We have not been able to

[^3]prove uniqueness of the measure of maximal entropy. Therefore, the deduction by Burton and Pemantle (1993) of the uniqueness of the measure of maximal entropy for domino tilings in $\mathbb{Z}^{2}$ (their Theorem 7.2) remains incomplete. However, a new and more general proof for the uniqueness of the measure of maximal entropy for domino tilings has been found by Sheffield (2003). The arguments in Burton and Pemantle (1993) can then be used to deduce the uniqueness of the measure of maximal entropy for spanning trees in $\mathbb{Z}^{2}$ (but not in higher dimensions, which remains open).

We give general background and definitions related to graphs, groups, and entropy in Section 2. In Section 3, we give our reformulation of the Matrix-Tree Theorem and its asymptotics, together with several examples. We give the formula for tree entropy as a determinant on infinite graphs in Section 7 , with applications. We prove the assertions on metric entropy in Section 5 .

Note added in proof: It has just been discovered that there is an error in Aldous and Lyons (2004). Namely, there is a gap in the proof that all unimodular random rooted graphs are random weak limits of finite graphs. This makes the proofs of certain results here incomplete. Remark 4.4, Proposition 4.5, and Theorem 4.6 will be complete when restricted to random weak limits of finite graphs, rather than claimed for all unimodular random rooted graphs.

## §2. Background.

We denote a (multi-)graph $G$ with vertex set V and edge set E by $G=(\mathrm{V}, \mathrm{E})$. When there is more than one graph under discussion, we write $\mathrm{V}(G)$ or $\mathrm{E}(G)$ to avoid ambiguity. We denote the degree of a vertex $x$ in a graph $G$ by $\operatorname{deg}_{G}(x)$. Unless stated otherwise, we assume all degrees finite. Simple random walk on $G$ is the Markov chain whose state space is V and whose transition probability from $x$ to $y$ equals the number of edges joining $x$ to $y$ divided by $\operatorname{deg}_{G}(x)$.

An infinite path in a tree that starts at any vertex and does not backtrack is called a ray. Two rays are equivalent if they have infinitely many vertices in common. An equivalence class of rays is called an end. More generally, an end of an infinite graph $G$ is an equivalence class of infinite simple paths in $G$, where two paths are equivalent if for every finite subgraph $K \subset G$, there is a connected component of $G \backslash K$ that intersects both paths.

Let $G$ be a graph. For a subgraph $H$, let its (internal) vertex boundary $\partial_{V} H$ be the set of vertices of $H$ that are adjacent to some vertex not in $H$. We say that $G$ is
amenable if there is an exhaustion $H_{1} \subset H_{2} \subset \cdots \subset H_{n} \subset \cdots$ with $\bigcup_{n} H_{n}=G$ and

$$
\lim _{n \rightarrow \infty} \frac{\left|\partial_{V} H_{n}\right|}{\left|\mathrm{V}\left(H_{n}\right)\right|}=0
$$

Such an exhaustion (or the sequence of its vertex sets) is called a Følner sequence. A finitely generated group is amenable if its Cayley graph is amenable. For example, every finitely generated abelian group is amenable. For more on amenability of graphs and groups, see Benjamini, Lyons, Peres, and Schramm (1999), hereinafter referred to as BLPS (1999).

A homomorphism $\varphi: G_{1} \rightarrow G_{2}$ from one graph $G_{1}=\left(\mathrm{V}_{1}, \mathrm{E}_{1}\right)$ to another $G_{2}=$ $\left(\mathrm{V}_{2}, \mathrm{E}_{2}\right)$ is a pair of maps $\varphi_{\mathrm{V}}: \mathrm{V}_{1} \rightarrow \mathrm{~V}_{2}$ and $\varphi_{\mathrm{E}}: \mathrm{E}_{1} \rightarrow \mathrm{E}_{2}$ such that $\varphi_{\mathrm{V}}$ maps the endpoints of $e$ to the endpoints of $\varphi_{\mathrm{E}}(e)$ for every edge $e \in \mathrm{E}_{1}$. When both maps $\varphi_{\mathrm{V}}: \mathrm{V}_{1} \rightarrow \mathrm{~V}_{2}$ and $\varphi_{\mathrm{E}}: \mathrm{E}_{1} \rightarrow \mathrm{E}_{2}$ are bijections, then $\varphi$ is called an isomorphism. When $G_{1}=G_{2}$, an isomorphism is called an automorphism. The group of all automorphisms of $G$ will be denoted by $\operatorname{Aut}(G)$. The action of a group $\Gamma$ on a graph $G$ by automorphisms is said to be transitive if there is only one $\Gamma$-orbit in $\mathrm{V}(G)$ and to be quasi-transitive if there are only finitely many orbits in $\mathrm{V}(G)$. A graph $G$ is transitive or quasi-transitive according as whether the corresponding action of $\operatorname{Aut}(G)$ is. For example, every Cayley graph is transitive.

The action of a group on a set is called free if the stabilizer of each element of the set is just the identity element of the group. For example, every group acts on itself freely by multiplication.

A locally compact group is called unimodular if its left Haar measure is also right invariant. In particular, every discrete countable group is unimodular. We call a graph $G$ unimodular if $\operatorname{Aut}(G)$ is unimodular, where $\operatorname{Aut}(G)$ is given the weak topology generated by its action on $G$. Every Cayley graph and, as Soardi and Woess (1990) and Salvatori (1992) proved, every quasi-transitive amenable graph is unimodular. See BLPS (1999) for more details on unimodular graphs.

We now recall some definitions pertaining to entropy. For simplicity, we restrict our discussion to groups acting on graphs, which is enough for our purposes. Suppose first that $\mu$ is a probability measure on a finite or countable set, $X$. The entropy of $\mu$ is

$$
\mathbf{H}(\mu):=-\sum_{x \in X} \mu(x) \log \mu(x) .
$$

For example, suppose that $\mu$ is a probability measure on the Borel sets of $2^{\mathrm{E}}:=\{0,1\}^{\mathrm{E}}$ in the product topology. As usual, we identify an element of $2^{\mathrm{E}}$ with the subset (or
"configuration") of edges where the value 1 is taken. If $H$ is a finite subgraph of $G$, write $\mu \upharpoonright H$ for the restriction of $\mu$ to the $\sigma$-field generated by the restrictions to $\mathrm{E}(H)$. That is, $\mu \upharpoonright H$ is defined on the finite set $2^{\mathrm{E}(H)}$ and has an entropy as above.

We shall twice use the following well-known lemma (see, e.g., Lemma 6.2 of Burton and Pemantle (1993) and p. 11 of Bollobás (2001) for the bound on the binomial coefficient sum).

Lemma 2.1. Let $Y$ be a finite set and $m$ be a positive integer. Write $\alpha:=m /|Y|$. Suppose that $\mu$ is a probability measure on $2^{Y} \times 2^{Y}$ that is supported on the set of pairs $\left(\omega_{1}, \omega_{2}\right)$ with $\left|\omega_{1} \triangle \omega_{2}\right| \leq m$. Let $\mu_{1}$ and $\mu_{2}$ be the coordinate marginals of $\mu$. Then

$$
\left|\mathbf{H}\left(\mu_{1}\right)-\mathbf{H}\left(\mu_{2}\right)\right| \leq \log \sum_{k=0}^{m}\binom{|Y|}{k} \leq|Y|(-\alpha \log \alpha-(1-\alpha) \log (1-\alpha))
$$

Suppose that the finite group $\Gamma$ acts on $X$ and preserves the measure $\mu$. Then the entropy of the pair $(\mu, \Gamma)$ is

$$
\mathbf{H}(\mu, \Gamma):=|\Gamma|^{-1} \mathbf{H}(\mu) .
$$

Finally, suppose that $\Gamma$ is a countable amenable finitely generated subgroup of Aut $(G)$. Let $\mu$ be a probability measure on $2^{\mathrm{E}}$ that is preserved by $\Gamma$. Let $\left\langle\Gamma_{n}\right\rangle$ be a F $\varnothing$ lner sequence in $\Gamma$ and $H$ be a finite subgraph of $G$ such that $\Gamma H=G$, provided such an $H$ exists. Then the (metric) entropy of the pair $(\mu, \Gamma)$, also called the $\Gamma$-entropy of $\mu$, is

$$
\mathbf{H}(\mu, \Gamma):=\lim _{n \rightarrow \infty}\left|\Gamma_{n}\right|^{-1} \mathbf{H}\left(\mu \upharpoonright\left(\Gamma_{n} H\right)\right) .
$$

This does not depend on the choice of $H$. See Ornstein and Weiss (1987) for more details on entropy.

## $\S$ 3. Asymptotic Complexity.

Recall that $\tau(G)$ denotes the complexity of the graph $G$, i.e., the number of spanning trees of $G$. Let $p_{k}(x ; G)$ denote the probability that simple random walk on $G$ started at $x$ is back at $x$ after $k$ steps.

We begin with a formula for the complexity of finite graphs.
Proposition 3.1. Suppose that $G$ is a finite connected graph. Then

$$
\log \tau(G)=-\log (2|\mathrm{E}(G)|)+\sum_{x \in \mathrm{~V}(G)} \log \operatorname{deg}_{G}(x)-\sum_{k \geq 1} \frac{1}{k}\left(\sum_{x \in \mathrm{~V}(G)} p_{k}(x ; G)-1\right)
$$

Proof. Let $P$ be the transition matrix for simple random walk on $G$ and $I$ be the identity matrix of the same size. As shown by Runge and Sachs (1974), we may rewrite (1.1) as

$$
\tau(G)=\frac{\prod_{x \in \mathrm{~V}(G)} \operatorname{deg}_{G}(x)}{\sum_{x \in \mathrm{~V}(G)} \operatorname{deg}_{G}(x)} \operatorname{det}^{\prime}(I-P)
$$

[the proof follows from looking at the coefficient of $t$ in $\operatorname{det}(I-P-t I)=\left(\operatorname{det} D_{G}\right)^{-1} \operatorname{det}\left(\Delta_{G}-\right.$ $t D_{G}$ ) and using the Matrix-Tree Theorem in its original form with cofactors]. Since the sum of the degrees of a graph equals twice the number of its edges, we obtain

$$
\begin{equation*}
\log \tau(G)=-\log (2|\mathrm{E}(G)|)+\sum_{x \in \mathrm{~V}(G)} \log \operatorname{deg}_{G}(x)+\log \operatorname{det}^{\prime}(I-P) \tag{3.1}
\end{equation*}
$$

Let $\Lambda$ be the multiset of eigenvalues of $P$ other than 1 (with multiplicities). Since $\Lambda \subset$ $[-1,1)$, we may rewrite the last term of (3.1) as

$$
\begin{aligned}
\log \operatorname{det}^{\prime}(I-P) & =\sum_{\lambda \in \Lambda} \log (1-\lambda)=-\sum_{\lambda \in \Lambda} \sum_{k \geq 1} \lambda^{k} / k \\
& =-\sum_{k \geq 1} \sum_{\lambda \in \Lambda} \lambda^{k} / k=-\sum_{k \geq 1} \frac{1}{k}\left(\operatorname{tr} P^{k}-1\right),
\end{aligned}
$$

where in the last step, we have used the fact that the eigenvalue 1 of $P$ has multiplicity 1 since $G$ is connected. Since $\operatorname{tr} P^{k}=\sum_{x \in \mathrm{~V}(G)} p_{k}(x ; G)$, the desired formula now follows from this and (3.1).

Remark 3.2. There is an extension of Proposition 3.1 to any irreducible Markov chain with transition matrix $P$. In this case, a spanning tree of the associated directed graph, with all edges leading towards a single vertex, is often called a "spanning arborescence". Let $\tau^{\prime}(P)$ be the sum over all spanning trees (with all possible roots) of the product of $P(e)$ over all $e$ in the tree. The analogue of Proposition 3.1 states that

$$
\log \tau^{\prime}(P)=-\sum_{k \geq 1} \frac{1}{k}\left(\sum_{x \in \vee(G)} p_{k}(x ; G)-1\right)
$$

This is reminiscent of a formula that appears in Lind and Tuncel (2001). In fact, combining their formula with ours, one gets an expression for the derivative at 1 of the reciprocal of the so-called stochastic zeta function of $P$.

A rooted graph $(G, x)$ is a graph $G$ with a distinguished vertex $x$ of $G$, called the root. A rooted isomorphism of rooted graphs is an isomorphism of the underlying
graphs that takes the root of one to the root of the other. We shall use the following notion of random weak convergence introduced by Benjamini and Schramm (2001) and studied further by Aldous and Steele (2004) and Aldous and Lyons (2004). Given a positive integer $R$, a finite rooted graph $H$, and a probability distribution $\rho$ on rooted graphs, let $p(R, H, \rho)$ denote the probability that $H$ is rooted isomorphic to the ball of radius $R$ about the root of a graph chosen with distribution $\rho$. If $(G, \rho)$ is a graph with probability distribution $\rho$ on its vertices, then $\rho$ induces naturally a distribution on rooted graphs, which we also denote by $\rho$; namely, the probability of $(G, x)$ is $\rho(x)$. For a finite graph $G$, let $U(G)$ denote the distribution of rooted graphs obtained by choosing a uniform random vertex of $G$ as root of $G$. Suppose that $\left\langle G_{n}\right\rangle$ is a sequence of finite graphs and that $\rho$ is a probability measure on rooted infinite graphs; in most practical cases, $\rho$ will be induced by a probability distribution on the vertices of a fixed infinite graph. We say the random weak limit of $\left\langle G_{n}\right\rangle$ is $\rho$ if for any positive integer $R$ and any finite graph $H$, we have $\lim _{n \rightarrow \infty} p\left(R, H, U\left(G_{n}\right)\right)=p(R, H, \rho)$. More generally, if $G_{n}$ are random finite graphs, then we say the random weak limit of $\left\langle G_{n}\right\rangle$ is $\rho$ if for any positive integer $R$, any finite graph $H$, and any $\epsilon>0$, we have $\lim _{n \rightarrow \infty} \mathbf{P}\left[\left|p\left(R, H, U\left(G_{n}\right)\right)-p(R, H, \rho)\right|>\epsilon\right]=0$. Note that only the component of the root matters for convergence to $\rho$. Thus, we may and shall assume that $\rho$ is concentrated on connected graphs. If $\rho$ is induced by a distribution on the vertices of a fixed transitive graph $G$, then the random weak limit depends only on $G$ and not on the root. In this case, we say that the random weak limit of $\left\langle G_{n}\right\rangle$ is $G$.

Given $R>0$ and a finite graph $G$, let $\nu_{R}(G)$ be the distribution of the number of edges in the ball of radius $R$ about a random vertex of $G$. Call a collection of finite graphs $G$ tight if for each $R$, the collection of corresponding distributions $\nu_{R}(G)$ is tight. Note that any tight collection of finite graphs has a subsequence that possesses a random weak limit.

Define the expected degree of a probability measure $\rho$ on rooted graphs to be

$$
\overline{\operatorname{deg}}(\rho):=\int \operatorname{deg}_{G}(x) d \rho(G, x)
$$

When the following integral converges, define the tree entropy of $\rho$ to be

$$
\mathbf{h}(\rho):=\int\left(\log \operatorname{deg}_{G}(x)-\sum_{k \geq 1} \frac{1}{k} p_{k}(x ; G)\right) d \rho(G, x)
$$

Our terminology is justified by Theorems 3.3 and 5.1 below. The integral converges, for example, when $\rho$ has finite expected degree, i.e., $\overline{\operatorname{deg}}(\rho)<\infty$, by virtue of the inequality between the arithmetic and geometric means; see also Corollary 3.9 and Proposition 4.5
below. If $\rho$ is induced by a fixed transitive graph, $G$, of degree $d$, we write

$$
\mathbf{h}(G):=\mathbf{h}(\rho)=\log d-\sum_{k \geq 1} \frac{1}{k} p_{k}(o ; G)
$$

for the tree entropy of $G$, where $o$ is any vertex of $G$.
Our main theorem in this section is the following. It also suggests thinking of $\mathbf{h}(\rho)$ as a normalized logarithm of the determinant of the Laplacian. See Theorem 4.1 for a more direct reason for thinking thus.

THEOREM 3.3. If $G_{n}$ are finite connected graphs with bounded average degree whose random weak limit is a probability measure $\rho$ on infinite rooted graphs, then

$$
\lim _{n \rightarrow \infty} \frac{1}{\left|\mathrm{~V}\left(G_{n}\right)\right|} \log \tau\left(G_{n}\right)=\mathbf{h}(\rho)
$$

The same limit holds in probability when $G_{n}$ are random with bounded expected average degree.

REMARK 3.4. If there is a homomorphism that is not an isomorphism from one transitive graph $G_{1}$ onto another $G_{2}$ of the same degree, then it is clear that $p_{k}\left(o ; G_{1}\right) \leq p_{k}\left(o ; G_{2}\right)$ for every $k$, with strict inequality for some $k$. Therefore, $\mathbf{h}\left(G_{1}\right)>\mathbf{h}\left(G_{2}\right)$. In particular, among all transitive graphs $G$ of degree $d$, the maximum of $\mathbf{h}(G)$ is achieved uniquely for $G$ the regular tree of degree $d$. This maximum value is calculated explicitly in Example 3.16. The uniqueness of the maximum, Theorem 3.3, and tightness imply that if a sequence of finite regular graphs $G_{n}$ of degree $d$ does not tend to the $d$-regular tree, $T$, then $\lim \inf _{n}\left|\mathrm{~V}\left(G_{n}\right)\right|^{-1} \log \tau\left(G_{n}\right)<\mathbf{h}(T)$; this is Theorem 4.5 of McKay (1983).

The only difficulty in deducing Theorem 3.3 from Proposition 3.1 is the interchange of limit and summation. In order to accomplish this, we shall use the following lemmas.

Lemma 3.5. Let $P$ be the transition matrix of a Markov chain. For $\alpha \in[0,1]$, define the transition matrix $Q:=\alpha I+(1-\alpha) P$. For a state $x$, let $p_{k}(x)$ and $q_{k}(x)$ denote the return probabilities to $x$ after $k$ steps when the Markov chains start at $x$, where the transition matrices are $P$ and $Q$, respectively. We have

$$
\begin{equation*}
\sum_{k} q_{k}(x) / k=-\log (1-\alpha)+\sum_{k} p_{k}(x) / k \tag{3.2}
\end{equation*}
$$

Proof. Write $(\bullet, \bullet)$ for the ordinary inner product in $\ell^{2}(V)$, where $V$ is the state space. Given $x \in V$ and $z \in(0,1)$, we have

$$
\sum_{k} q_{k}(x) z^{k} / k=-\left([\log (I-z Q)] \mathbf{1}_{\{x\}}, \mathbf{1}_{\{x\}}\right)
$$

$$
\begin{aligned}
& =-\left([\log ((1-z \alpha) I-z(1-\alpha) P)] \mathbf{1}_{\{x\}}, \mathbf{1}_{\{x\}}\right) \\
& =-\left(\left[\log \left(I-\frac{z(1-\alpha)}{1-z \alpha} P\right)\right] \mathbf{1}_{\{x\}}, \mathbf{1}_{\{x\}}\right)-\log (1-z \alpha)\left(\mathbf{1}_{\{x\}}, \mathbf{1}_{\{x\}}\right) \\
& =-\log (1-z \alpha)+\sum_{k} p_{k}(x)\left(\frac{z(1-\alpha)}{1-z \alpha}\right)^{k} \frac{1}{k}
\end{aligned}
$$

Letting $z \uparrow 1$, we obtain the desired equation.
Next we give a universal bound for the rate of convergence of $p_{k}(x ; G)$ to the stationary probability $\operatorname{deg}_{G}(x) / 2|\mathrm{E}(G)|$ for finite graphs and to 0 for infinite graphs. In the case of infinite graphs, such a result is first due to Carlen, Kusuoka, and Stroock (1987). Our argument is a modification of that of Coulhon (2000) and seems not to be written anywhere for the case of finite graphs, although there is some overlap with the treatment of the special case in Example 2.3.1 of Saloff-Coste (1997). For sharper bounds that depend on more information about the graph, see, e.g., Theorems 3.3.11 and 2.3.1 of Saloff-Coste (1997) for the finite case and Barlow, Coulhon, and Grigor'yan (2001) for the infinite case. See also Morris and Peres (2004).

Lemma 3.6. Suppose that $Q$ is a transition matrix of a Markov chain that is reversible with respect to a positive measure $\pi$. If $\pi$ is finite, then we assume that $\pi$ is normalized to be a probability measure. Assume that $c:=\inf \{\pi(x) Q(x, y) ; x \neq y$ and $Q(x, y)>0\}>0$ and that $a:=\inf _{x} Q(x, x)>0$. For all states $x$ and all $k \geq 0$, we have

$$
\begin{equation*}
\left|\frac{Q^{k}(x, x)}{\pi(x)}-1\right| \leq \min \left\{\frac{1}{a c \sqrt{k+1}}, \frac{1}{2 a^{2} c^{2}(k+1)}\right\} \tag{3.3}
\end{equation*}
$$

if $\pi$ is finite and

$$
\begin{equation*}
\frac{Q^{k}(x, x)}{\pi(x)} \leq \frac{1}{a c \sqrt{k+1}} \tag{3.4}
\end{equation*}
$$

if $\pi$ is infinite.
Proof. Write $V$ for the state space and $E$ for the set of pairs $(x, y)$ where $Q(x, y)>0$ and $x \neq y$. Write

$$
c_{2}(x, y):=\pi(x) Q^{2}(x, y)
$$

and note that for $(x, y) \in E$, we have

$$
c_{2}(x, y) \geq \pi(x)[Q(x, x) Q(x, y)+Q(x, y) Q(y, y)] \geq 2 a c .
$$

Define the inner product $\left(f_{1}, f_{2}\right)_{\pi}:=\sum_{x} f_{1}(x) f_{2}(x) \pi(x)$ on $\ell^{2}(V, \pi)$.

The case where $\pi$ is infinite is simpler, so we treat that first. Let $f$ be a function on $V$ with finite support. Let $x_{0}$ be a vertex where $|f|$ achieves its maximum. Then

$$
\begin{equation*}
\|f\|_{\infty}=\left|f\left(x_{0}\right)\right| \leq \frac{1}{2} \sum_{(x, y) \in E}|f(x)-f(y)| \leq \frac{1}{2} \sum_{x, y \in V} c_{2}(x, y)|f(x)-f(y)| /(2 a c), \tag{3.5}
\end{equation*}
$$

where the factor $1 / 2$ arises from counting each pair $(x, y)$ in each order. Applying (3.5) to the function $f^{2}$, we obtain

$$
\begin{aligned}
(2 a c)^{2}\|f\|_{\infty}^{4} & \leq\left(\frac{1}{2} \sum_{x, y \in V} c_{2}(x, y)|f(x)-f(y)| \cdot|f(x)+f(y)|\right)^{2} \\
& \leq\left(\frac{1}{2} \sum_{x, y \in V} c_{2}(x, y)[f(x)-f(y)]^{2}\right)\left(\frac{1}{2} \sum_{x, y \in V} c_{2}(x, y)[f(x)+f(y)]^{2}\right) \\
& =\left(\left(I-Q^{2}\right) f, f\right)_{\pi}\left(\left(I+Q^{2}\right) f, f\right)_{\pi}
\end{aligned}
$$

by the Cauchy-Schwarz inequality and some straightforward algebra. Therefore, if $(f, f)_{\pi} \leq$ 1, we have $2(a c)^{2}\|f\|_{\infty}^{4} \leq\left(\left(I-Q^{2}\right) f, f\right)_{\pi}$. Apply this inequality to the functions $Q^{l} f$ for $l=0, \ldots, k$ and sum the resulting inequalities to obtain

$$
\begin{aligned}
(k+1) 2(a c)^{2}\left\|Q^{k} f\right\|_{\infty}^{4} & \leq 2(a c)^{2} \sum_{l=0}^{k}\left\|Q^{l} f\right\|_{\infty}^{4} \leq \sum_{l=0}^{k}\left(\left(I-Q^{2}\right) Q^{l} f, Q^{l} f\right)_{\pi} \\
& =\sum_{l=0}^{k}\left(\left(I-Q^{2}\right) Q^{2 l} f, f\right)_{\pi}=\left(\left(I-Q^{2 k+2}\right) f, f\right)_{\pi} \leq 1
\end{aligned}
$$

for $(f, f)_{\pi} \leq 1$. This shows that the norm of $Q^{k}: \ell^{2}(V, \pi) \rightarrow \ell^{\infty}(V)$ is bounded by

$$
\beta_{k}:=\left[(2 k+2)(a c)^{2}\right]^{-1 / 4} .
$$

The same bound holds for $Q^{k}: \ell^{1}(V, \pi) \rightarrow \ell^{2}(V, \pi)$ by duality. Therefore, considering $Q^{2 k}=Q^{k} \circ Q^{k}$, we find that the norm of $Q^{2 k}: \ell^{1}(V, \pi) \rightarrow \ell^{\infty}(V)$ is at most $\beta_{k}^{2}$, while the norm of $Q^{2 k+1}: \ell^{1}(V, \pi) \rightarrow \ell^{\infty}$ is at most $\beta_{k} \beta_{k+1}$. Applying these inequalities to $f:=\mathbf{1}_{\{x\}} / \pi(x)$ gives (3.4).

The case of finite $\pi$ is quite similar. The essential difference is that we work with $\ell_{0}^{2}(V, \pi)$, the orthogonal complement of the constants in $\ell^{2}(V, \pi)$. Note that $\mathbf{1}$ is an eigenfunction of $Q$ and that $\ell_{0}^{2}(V, \pi)$ is invariant under $Q$. We may still conclude (3.5) for all $f$ that have at least one nonnegative value and at least one nonpositive value, such as all $f \in \ell_{0}^{2}(V, \pi)$.

Take $f \in \ell_{0}^{2}(V, \pi)$. Notice that $\sum_{x, y \in V} c_{2}(x, y)=\sum_{x \in V} \pi(x)=1$. Thus, we have from (3.5) that

$$
\begin{equation*}
(2 a c)^{2}\|f\|_{\infty}^{2} \leq \frac{1}{2} \sum_{x, y \in V} c_{2}(x, y)[f(x)-f(y)]^{2}=\left(\left(I-Q^{2}\right) f, f\right)_{\pi} \tag{3.6}
\end{equation*}
$$

Alternatively, we may apply (3.5) to the function $\operatorname{sgn}(f) f^{2}$. Using the trivial inequality

$$
\left|\operatorname{sgn}(s) s^{2}-\operatorname{sgn}(t) t^{2}\right| \leq|s-t| \cdot(|s|+|t|)
$$

valid for any real numbers $s$ and $t$, we obtain that

$$
\begin{aligned}
(2 a c)^{2}\|f\|_{\infty}^{4} & \leq\left(\frac{1}{2} \sum_{x, y \in V} c_{2}(x, y)|f(x)-f(y)| \cdot(|f(x)|+|f(y)|)\right)^{2} \\
& \leq\left(\left(I-Q^{2}\right) f, f\right)_{\pi}\left(\left(I+Q^{2}\right)|f|,|f|\right)_{\pi}
\end{aligned}
$$

Putting both these estimates together, we get

$$
2(a c)^{2} \max \left\{2\|f\|_{\infty}^{2},\|f\|_{\infty}^{4}\right\} \leq\left(\left(I-Q^{2}\right) f, f\right)_{\pi}
$$

for $(f, f)_{\pi}=1$. As before, this implies that

$$
(k+1) 2(a c)^{2} \max \left\{2\left\|Q^{k} f\right\|_{\infty}^{2},\left\|Q^{k} f\right\|_{\infty}^{4}\right\} \leq 1
$$

which shows that the norm of $Q^{k}: \ell_{0}^{2}(V, \pi) \rightarrow \ell^{\infty}(V)$ is bounded by

$$
\alpha_{k}:=\min \left\{\left[(2 a c)^{2}(k+1)\right]^{-1 / 2},\left[(2 k+2)(a c)^{2}\right]^{-1 / 4}\right\}
$$

Let $T: \ell^{2}(V, \pi) \rightarrow \ell_{0}^{2}(V, \pi)$ be the orthogonal projection $T f:=f-(f, \mathbf{1})_{\pi} \mathbf{1}$. Given what we have shown, we see that the norm of $Q^{k} T: \ell^{2}(V, \pi) \rightarrow \ell^{\infty}(V)$ is bounded by $\alpha_{k}$. By duality, the same bound holds for $T Q^{k}: \ell^{1}(V, \pi) \rightarrow \ell^{2}(V, \pi)$. As before, we deduce that the norm of $Q^{k} T Q^{k}: \ell^{1}(V, \pi) \rightarrow \ell^{\infty}(V)$ is at most $\alpha_{k}^{2}$ and the norm of $Q^{k} T Q^{k+1}: \ell^{1}(V, \pi) \rightarrow \ell^{\infty}$ is at most $\alpha_{k} \alpha_{k+1}$. Applying these inequalities to $f:=\mathbf{1}_{\{x\}} / \pi(x)$ gives (3.3).

Remark 3.7. In the infinite case, we do not actually need to assume that $a>0$. That is, suppose that $Q$ is a transition matrix of a Markov chain that is reversible with respect to a positive measure $\pi$. Assume that $c:=\inf \{\pi(x) Q(x, y) ; x \neq y$ and $Q(x, y)>0\}>0$. If $\pi$ is infinite, then

$$
Q^{k}(x, x) / \pi(x) \leq \frac{4}{c \sqrt{k+1}}
$$

To see this, we have only to establish that

$$
\left|f\left(x_{0}\right)\right| \leq(1 / c) \sum_{x, y \in V} c_{2}(x, y)|f(x)-f(y)|
$$

as a substitute for (3.5). Let $E_{2}:=\left\{(x, y) ; Q^{2}(x, y)>0\right\}$. Because $\pi$ is infinite, for any finite set $S$ of states, there is some $y$ such that $Q(y, S) Q\left(y, S^{c}\right)>0$, where $Q(y, A):=$ $\sum_{z \in A} Q(y, z)$. Note that $Q(y, S)+Q\left(y, S^{c}\right)=1$. Either $Q(y, S)$ or $Q\left(y, S^{c}\right)$ is at least $1 / 2$ and $\pi(y)$ times the other is at least $c$, whence

$$
\pi(y) Q(y, S) Q\left(y, S^{c}\right) \geq c / 2
$$

It follows that

$$
\begin{aligned}
\sum_{x \in S} \sum_{z \notin S} c_{2}(x, z) & =\sum_{x \in S} \pi(x) \sum_{z \notin S} Q^{2}(x, z)=\sum_{x \in S} \pi(x) \sum_{y} \sum_{z \notin S} Q(x, y) Q(y, z) \\
& =\sum_{y} \pi(y) Q(y, S) Q\left(y, S^{c}\right) \geq c / 2
\end{aligned}
$$

That is, for any cutset of edges $e \in E_{2}$ that separates $x_{0}$ from infinity in the graph $\left(V, E_{2}\right)$, the sum of $c_{2}(e)$ over the cutset is at least $c / 2$. Therefore, the max-flow min-cut theorem provides a flow $\theta$ from $x_{0}$ to infinity of value $c / 2$ that is bounded by $c_{2}$ on each edge in $E_{2}$. This yields

$$
\begin{aligned}
\left|f\left(x_{0}\right)\right| c & =\left|\sum_{(x, y) \in E_{2}}[f(x)-f(y)] \theta(x, y)\right| \leq \sum_{(x, y) \in E_{2}}|f(x)-f(y)| \cdot|\theta(x, y)| \\
& \leq \sum_{(x, y) \in E_{2}}|f(x)-f(y)| c_{2}(x, y)
\end{aligned}
$$

as desired. (Recall that each pair $(x, y)$ is counted twice in the sum.)
REMARK 3.8. The proofs as given show the very same bounds on the more general quantities $\left|Q^{k}(y, x) / \pi(y)-1\right|$ or $Q^{k}(y, x) / \pi(y)$ for all states $x, y$ and all $k \geq 0$.

Corollary 3.9. If $\rho$ is a probability measure on infinite rooted graphs with finite expected degree, then $\mathbf{h}(\rho)$ is finite.

Proof. For a graph $G$ with transition matrix $P$, let $Q:=(I+P) / 2$. Then $Q$ is the transition matrix of the graph $G^{\prime}$ obtained from $G$ by adding loops to each vertex so as to double its degree. Write $q_{k}(x ; G):=p_{k}\left(x ; G^{\prime}\right)$. Lemma 3.5 tells us that

$$
\sum_{k} q_{k}(x ; G) / k=\log 2+\sum_{k} p_{k}(x ; G) / k
$$

In addition, $Q$ is reversible with respect to the measure $x \mapsto \operatorname{deg}_{G}(x)$, so that Lemma 3.6 applies with $a \geq 1 / 2$ and $c \geq 1 / 2$ (equality holds in both cases when $G$ has no loops) to yield

$$
q_{k}(x ; G) \leq \frac{4}{\sqrt{k+1}} \operatorname{deg}_{G}(x)
$$

Therefore,

$$
\begin{aligned}
\mathbf{h}(\rho) & =\log 2+\int\left(\log \operatorname{deg}_{G}(x)-\sum_{k \geq 1} q_{k}(x ; G) / k\right) d \rho(G, x) \\
& \geq \log 2+\int\left(\log \operatorname{deg}_{G}(x)-\sum_{k \geq 1} \frac{4}{k \sqrt{k+1}} \operatorname{deg}_{G}(x)\right) d \rho(G, x) \\
& =\log 2+\int \log \operatorname{deg}_{G}(x) d \rho(G, x)-\overline{\operatorname{deg}}(\rho) \sum_{k \geq 1} \frac{4}{k \sqrt{k+1}} .
\end{aligned}
$$

This gives the corollary by the inequality between the arithmetic and geometric means.
The following lemma is well known.
Lemma 3.10. Suppose that $Y_{n}$ are real-valued random variables that converge in distribution to $Y$ and that $\sup _{n} \mathbf{E}\left[\left|Y_{n}\right|\right]<\infty$. Then for all continuous functions $f: \mathbb{R} \rightarrow \mathbb{R}$ such that $\lim _{|x| \rightarrow \infty}|f(x)| /|x|=0$, we have $\lim _{n \rightarrow \infty} \mathbf{E}\left[f\left(Y_{n}\right)\right]=\mathbf{E}[f(Y)]$.

Proof. The hypotheses easily imply that $f\left(Y_{n}\right)$ form a uniformly integrable set of random variables. The continuity of $f$ ensures that $f\left(Y_{n}\right)$ converge in distribution to $f(Y)$. Together, these imply the conclusion.

Proof of Theorem 3.3. We claim that the more general second statement of the theorem follows from the first statement. The space of rooted-isomorphism classes of graphs is complete, separable and metrizable (see Aldous and Steele (2004) for some of the details). Thus, under the hypothesis of the second statement, we may assume by Skorohod's theorem (see, e.g., Theorem 11.7.2 of Dudley (1989)) that $G_{n}$ are defined on a common probability space such that a.s., $G_{n}$ has a random weak limit $\rho$. Therefore, if the first statement holds, then so does the second.

We now prove the first statement. Double the degree of each vertex in $G_{n}$ by adding loops to give graphs $G_{n}^{\prime}$. These new graphs have transition matrices $Q_{n}:=\left(I+P_{n}\right) / 2$, where $P_{n}$ is the transition matrix of $G_{n}$. Furthermore, the random weak limit of $G_{n}^{\prime}$ is $\rho^{\prime}$, where $\rho^{\prime}$ is obtained from $\rho$ by doubling the degree of each vertex by adding loops. By Lemma 3.5, we have $\mathbf{h}\left(\rho^{\prime}\right)=\mathbf{h}(\rho)$. Also, $\tau\left(G_{n}^{\prime}\right)=\tau\left(G_{n}\right)$, so it suffices to show that

$$
\lim _{n \rightarrow \infty} \frac{1}{\left|\mathrm{~V}\left(G_{n}^{\prime}\right)\right|} \log \tau\left(G_{n}^{\prime}\right)=\mathbf{h}\left(\rho^{\prime}\right)
$$

Let $d$ be an upper bound for the average degree of $G_{n}^{\prime}$, i.e., for all $n$,

$$
\begin{equation*}
2\left|\mathrm{E}\left(G_{n}^{\prime}\right)\right| \leq d\left|\vee\left(G_{n}^{\prime}\right)\right|, \tag{3.7}
\end{equation*}
$$

so that $\left|\mathrm{V}\left(G_{n}^{\prime}\right)\right|^{-1} \log \left(2\left|\mathrm{E}\left(G_{n}^{\prime}\right)\right|\right) \rightarrow 0$ as $n \rightarrow \infty$. Since the degree of a random vertex in $G_{n}^{\prime}$ converges in distribution to the degree of the root under $\rho^{\prime}$, it follows that

$$
\frac{1}{\left|\mathrm{~V}\left(G_{n}^{\prime}\right)\right|} \sum_{x \in \mathrm{~V}\left(G_{n}^{\prime}\right)} \log \operatorname{deg}_{G_{n}^{\prime}}(x) \rightarrow \int \log \operatorname{deg}_{G}(x) d \rho^{\prime}(G, x)
$$

by Lemma 3.10 [use there $f:=\log ^{+}$and $Y_{n}$ equals the degree of a uniform vertex in $G_{n}^{\prime}$ ]. Thus, in using Proposition 3.1, we have left to show only that

$$
\lim _{n \rightarrow \infty} \sum_{k \geq 1}\left|\mathrm{~V}\left(G_{n}^{\prime}\right)\right|^{-1} \frac{1}{k}\left(\sum_{x \in \mathrm{~V}\left(G_{n}^{\prime}\right)} p_{k}\left(x ; G_{n}^{\prime}\right)-1\right)=\int \sum_{k \geq 1} \frac{1}{k} p_{k}(x ; G) d \rho^{\prime}(G, x)
$$

By definition and the hypothesis, we have for each $k$ that

$$
\lim _{n \rightarrow \infty}\left|\mathrm{~V}\left(G_{n}^{\prime}\right)\right|^{-1}\left(\sum_{x \in \mathrm{~V}\left(G_{n}^{\prime}\right)} p_{k}\left(x ; G_{n}^{\prime}\right)-1\right)=\int p_{k}(x ; G) d \rho^{\prime}(G, x)
$$

Lemma 3.6 applies to $G_{n}^{\prime}$ with stationary probability measure $x \mapsto \operatorname{deg}_{G_{n}^{\prime}}(x) /\left[2\left|\mathrm{E}\left(G_{n}^{\prime}\right)\right|\right]$ and constants $a \geq 1 / 2, c \geq 1 /\left[4\left|\mathrm{E}\left(G_{n}^{\prime}\right)\right|\right]$ to yield

$$
\left|\mathrm{V}\left(G_{n}^{\prime}\right)\right|^{-1}\left|\sum_{x \in \mathrm{~V}\left(G_{n}\right)} p_{k}\left(x ; G_{n}^{\prime}\right)-1\right| \leq \frac{4 d}{\sqrt{k+1}}
$$

Hence Weierstrass' M-test justifies the interchange of limit and summation and we are done.

REmARK 3.11. A similar result holds for weighted graphs. That is, given a graph $G$ whose edges are assigned positive weights, write $\tau(G)$ for the sum of the weights of its spanning trees, where the weight of a spanning tree is the product of the weights of its edges. Let the weight of a vertex be the sum of the weights of its incident edges. The random walk corresponding to a weighted graph has transition probability from $x$ to $y$ equal to the sum of the weights of the edges joining $x$ to $y$ divided by the weight of $x$. If a sequence of weighted connected finite graphs with weights bounded above and away from 0 and with bounded average vertex weight has a random weak limit $\rho$ on weighted rooted infinite graphs, then the conclusion of Theorem 3.3 holds, where $\mathbf{h}(\rho)$ is defined using the weight
of the root in place of its degree and by using the weighted random walk on the limit graph.

We now illustrate some of the consequences of Theorem 3.3. Our first result concerns the stability of the asymptotic complexity, for which we prepare with a lemma related to tightness.

Let $B_{R}(x)=\left(\mathrm{V}_{R}(x), \mathrm{E}_{R}(x)\right)$ denote the ball of radius $R$ about a vertex $x$.
Lemma 3.12. Let $\left\langle G_{n}\right\rangle$ be a sequence of finite graphs with vertex subsets $W_{n} \subset \mathrm{~V}\left(G_{n}\right)$ satisfying $\lim _{n \rightarrow \infty}\left|W_{n}\right| / v_{n}=0$, where $v_{n}:=\left|\mathrm{V}\left(G_{n}\right)\right|$. For $R>0$, let

$$
s_{n}(R, t):=\left|\left\{x \in \mathrm{~V}\left(G_{n}\right) ;\left|\mathrm{V}_{R}(x)\right|>t\right\}\right|
$$

Let also

$$
w_{n}(R):=\left|\left\{x \in \mathrm{~V}\left(G_{n}\right) ; \mathrm{V}_{R}(x) \cap W_{n} \neq \varnothing\right\}\right|
$$

If for each $R>0$, we have

$$
\begin{equation*}
\lim _{t \rightarrow \infty} \limsup _{n \rightarrow \infty} s_{n}(R, t) / v_{n}=0 \tag{3.8}
\end{equation*}
$$

then for each $R>0$, we have $\lim _{n \rightarrow \infty} w_{n}(R) / v_{n}=0$.
Proof. We have that $\mathrm{V}_{R}(x) \cap W_{n} \neq \varnothing$ iff $x$ lies in a ball of radius $R$ about some vertex of $W_{n}$. If we partition $W_{n}$ in two, one part consisting of those vertices $x$ with $\left|\mathrm{V}_{R}(x)\right| \leq t$ and the other part consisting of the rest, then we deduce that

$$
w_{n}(R) \leq t\left|W_{n}\right|+s_{n}(2 R, t)
$$

for any $R>0$ and $t>0$. Thus,

$$
\limsup _{n \rightarrow \infty} w_{n}(R) / v_{n} \leq \limsup _{n \rightarrow \infty} s_{n}(2 R, t) / v_{n}
$$

If we now let $t \rightarrow \infty$, we obtain the desired result.
Note that (3.8) holds if $\left\langle G_{n}\right\rangle$ has a random weak limit. In fact, (3.8) is just slightly weaker than tightness, since this condition counts vertices, while tightness counts edges.

Corollary 3.13. Let $\left\langle G_{n}\right\rangle$ be a tight sequence of finite connected graphs with bounded average degree such that $\lim _{n \rightarrow \infty}\left|\mathrm{~V}\left(G_{n}\right)\right|^{-1} \log \tau\left(G_{n}\right)=h$. If $\left\langle G_{n}^{\prime}\right\rangle$ is a sequence of connected subgraphs of $\left\langle G_{n}\right\rangle$ such that

$$
\lim _{n \rightarrow \infty}\left|\mathrm{~V}\left(G_{n}\right)\right|^{-1}\left|\left\{x \in \mathrm{~V}\left(G_{n}^{\prime}\right) ; \operatorname{deg}_{G_{n}^{\prime}}(x)=\operatorname{deg}_{G_{n}}(x)\right\}\right|=1
$$

then $\lim _{n \rightarrow \infty}\left|\mathrm{~V}\left(G_{n}^{\prime}\right)\right|^{-1} \log \tau\left(G_{n}^{\prime}\right)=h$.
Proof. By taking a subsequence, if necessary, we may assume (by tightness) that $\left\langle G_{n}\right\rangle$ has a random weak limit, $\rho$. By Theorem 3.3, we have $h=\mathbf{h}(\rho)$. Let $W_{n}:=\{x \in$ $\left.\mathrm{V}\left(G_{n}^{\prime}\right) ; \operatorname{deg}_{G_{n}^{\prime}}(x) \neq \operatorname{deg}_{G_{n}}(x)\right\}$. Then (3.8) holds because of tightness, whence $\left\langle G_{n}^{\prime}\right\rangle$ also has the random weak limit $\rho$ by Lemma 3.12. Hence Theorem 3.3 applies again to give the desired conclusion.

We next illustrate the flexibility of Theorem 3.3 by considering hybrid graphs as follows.

Corollary 3.14. Let $\left\langle G_{n}\right\rangle$ and $\left\langle G_{n}^{\prime}\right\rangle$ be tight sequences of finite connected graphs with bounded average degree such that

$$
\lim _{n \rightarrow \infty}\left|\mathrm{~V}\left(G_{n}\right)\right|^{-1} \log \tau\left(G_{n}\right)=h \quad \text { and } \quad \lim _{n \rightarrow \infty}\left|\mathrm{~V}\left(G_{n}^{\prime}\right)\right|^{-1} \log \tau\left(G_{n}\right)=h^{\prime}
$$

Suppose that

$$
\lim _{n \rightarrow \infty} \frac{\left|\mathrm{~V}\left(G_{n}\right)\right|}{\left|\mathrm{V}\left(G_{n}\right)\right|+\left|\mathrm{V}\left(G_{n}^{\prime}\right)\right|}=\alpha \in[0,1]
$$

Let $H_{n}$ be formed by connecting disjoint copies of $G_{n}$ and $G_{n}^{\prime}$ with o $\left(\left|\mathrm{V}\left(G_{n}\right)\right|+\left|\mathrm{V}\left(G_{n}^{\prime}\right)\right|\right)$ edges in any manner that gives a sequence of connected graphs. Then

$$
\lim _{n \rightarrow \infty} \frac{1}{\left|\mathrm{~V}\left(H_{n}\right)\right|} \log \tau\left(H_{n}\right)=\alpha h+(1-\alpha) h^{\prime}
$$

Proof. By taking subsequences, if necessary, we may assume that $\left\langle G_{n}\right\rangle$ and $\left\langle G_{n}^{\prime}\right\rangle$ have random weak limits, $\rho$ and $\rho^{\prime}$. By Theorem [3.3, we have $h=\mathbf{h}(\rho)$ and $h^{\prime}=\mathbf{h}\left(\rho^{\prime}\right)$. By Lemma 3.12, the random weak limit of $H_{n}$ is $\alpha \rho+(1-\alpha) \rho^{\prime}$. Thus Theorem 3.3 gives the desired conclusion.

Given probability measures $\rho_{n}$ and $\rho$ on rooted graphs, we say that $\rho_{n}$ converges weakly to $\rho$ if $p\left(R, H, \rho_{n}\right) \rightarrow p(R, H, \rho)$ as $n \rightarrow \infty$ for any positive integer $R$ and any finite graph $H$. It is not hard to show that tree entropy is a continuous functional when one bounds the expected degree:

Proposition 3.15. If $\rho_{n}$ converges weakly to $\rho$ as $n \rightarrow \infty$ with $\sup _{n} \overline{\operatorname{deg}}\left(\rho_{n}\right)<\infty$, then $\mathbf{h}\left(\rho_{n}\right) \rightarrow \mathbf{h}(\rho)$ as $n \rightarrow \infty$.

Proof. As in the proof of Theorem 3.3, we may double the degree of each vertex by adding loops without changing the tree entropies. By Lemma 3.10 and our assumption of bounded expected degree, we have $\int \log \operatorname{deg}_{G}(x) d \rho_{n}(G, x) \rightarrow \int \log \operatorname{deg}_{G}(x) d \rho(G, x)$. Weak convergence itself already guarantees that $\int p_{k}(x ; G) d \rho_{n}(G, x) \rightarrow \int p_{k}(x ; G) d \rho(G, x)$ for each $k$. The bounded expected degree and Lemma 3.6 allow us to apply Weierstrass' M-test to get the desired conclusion.

We now give several explicit examples illustrating the use of tree entropy, beginning with the transitive case.

In order to evaluate the infinite sum appearing in $\mathbf{h}(G)$, the following integral is sometimes useful. Let $\mathcal{G}(z):=\mathcal{G}(z ; G):=\sum_{k \geq 0} p_{k}(o ; G) z^{k}$ be the return probability generating function of the graph $G$. Then clearly

$$
\begin{equation*}
\sum_{k \geq 1} \frac{1}{k} p_{k}(o ; G)=\int_{0}^{1} \frac{\mathcal{G}(z)-1}{z} d z \tag{3.9}
\end{equation*}
$$

Example 3.16. For a group $\Gamma$ with a given generating set, let $\ell(\Gamma)$ denote the length of the smallest (nonempty) reduced word in the generating elements that represents the identity, i.e., the girth of the Cayley graph of $\Gamma$. Suppose that $\Gamma_{n}$ are finite groups, each generated by $s$ elements, such that $\lim _{n \rightarrow \infty} \ell\left(\Gamma_{n}\right)=\infty$. Then the Cayley graphs $G_{n}$ of $\Gamma_{n}$ have a random weak limit equal to the usual Cayley graph $G$ of the free group $\Gamma$ on $s$ letters, i.e., the regular tree of degree $2 s$. By Theorem 3.3, it follows that

$$
\lim _{n \rightarrow \infty}\left|\Gamma_{n}\right|^{-1} \log \tau\left(G_{n}\right)=\mathbf{h}(G)
$$

independently of the particular choice of $\Gamma_{n}$. To evaluate $\mathbf{h}(G)$, we use the fact that the return series is

$$
\mathcal{G}(z ; G)=\frac{1-s+\sqrt{s^{2}-(2 s-1) z^{2}}}{1-z^{2}}
$$

a result of Kesten (1959). The integrand in (3.9) then has an "elementary" antiderivative, which yields

$$
\mathbf{h}(G)=\log \frac{(2 s-1)^{2 s-1}}{[4 s(s-1)]^{s-1}}
$$

For example, for $s=2$, we find $\mathbf{h}(G)=\log (3 / 2)^{3}$. More generally, when $G$ is the regular tree of degree $d$, we have

$$
\mathcal{G}(z ; G)=\frac{2(d-1)}{d-2+\sqrt{d^{2}-4(d-1) z^{2}}}
$$

(see, e.g., Lemma 1.24 of Woess (2000)), whence

$$
\mathbf{h}(G)=\log \frac{(d-1)^{d-1}}{[d(d-2)]^{d / 2-1}}
$$

For example, $\mathbf{h}(G)=\log (4 / \sqrt{3})$ if $d=3$. As we mentioned in the introduction, this calculation of the asymptotic complexity of regular graphs with girth tending to infinity was first done by McKay (1983) under additional hypotheses on the graphs. For the case of
(uniformly) random $d$-regular graphs, where it is easy to see that they have a random weak limit equal to the $d$-regular tree, $G$, we obtain that the asymptotic complexity tends in probability to $\mathbf{h}(G)$; this was also shown by McKay (1983), who showed in McKay (1981) that random regular graphs satisfy his extra hypotheses.

Example 3.17. The usual Erdős-Rényi model of random graphs, $\mathcal{G}(n, p)$, is a graph on $n$ vertices, each pair of which is connected by an edge with probability $p$, independently of other edges. Other language for this is $\operatorname{Bernoulli}(p)$ bond percolation on the complete graph $K_{n}$. Fix $c>1$. The well-known fact that the entire graph $\mathcal{G}(n, c / n)$ has a random weak limit $\operatorname{PGW}(c)$ is proved explicitly in Aldous (1998), where $\operatorname{PGW}(c)$ is the law of a rooted Galton-Watson tree with Poisson (c) offspring distribution. It is well known that with probability approaching 1 as $n \rightarrow \infty$, there is a unique connected component, called the giant component, of $\mathcal{G}(n, c / n)$, that has $\Omega(n)$ vertices. See, e.g., Bollobás (2001). Also, the giant component has a random weak limit $\operatorname{PGW}^{*}(c)$, which is $\operatorname{PGW}(c)$ conditioned on nonextinction. This limit of the giant component is folklore and seems not to be written anywhere. Let $f(c):=\mathbf{h}\left(\mathrm{PGW}^{*}(c)\right)$. We also define $\mathrm{PGW}^{*}(1)$ to be the weak limit of $\mathrm{PGW}^{*}(c)$ as $c \downarrow 1$. Since $\mathrm{PGW}^{*}(1)$ is the random weak limit of trees (more specifically, of the uniform spanning tree on $K_{n}$ ) by Grimmett (1980/81), we have $f(1)=0$ (which also follows from Theorem 4.6 below). By Proposition 3.15, $f$ is continuous on $[1, \infty)$. We wonder whether $f$ is strictly increasing on $[1, \infty)$ and real analytic on $(1, \infty)$. The fact that $f(c)>0$ for $c>1$ follows from Theorem 4.6 below, together with the well-known fact that $\mathrm{PGW}^{*}(c)$ has infinitely many ends a.s. for $c>1$. It would be interesting to see an explicit formula for $f$.

An additional useful tool for calculation is explained in Section 9 of Woess (2000). Namely, as explained there, if we let $\mathbf{r}$ be the radius of convergence of $\mathcal{G}(\cdot)$, then there is a strictly increasing function $\Phi:=\Phi_{G}:[0, \mathbf{r} \mathcal{G}(\mathbf{r})) \rightarrow \mathbb{R}$ such that

$$
\begin{equation*}
\mathcal{G}(z)=\Phi(z \mathcal{G}(z)) \tag{3.10}
\end{equation*}
$$

on $[0, \mathbf{r} \mathcal{G}(\mathbf{r}))$. We are grateful to W . Woess for pointing out to us the remainder of this paragraph. In many cases, it is easier to find $\Phi$ than to (solve and) find $\mathcal{G}$. Note that from (3.10), we have

$$
\begin{equation*}
\mathcal{G}(1)=\Phi(\mathcal{G}(1)) ; \tag{3.11}
\end{equation*}
$$

it can be much easier to solve for $\mathcal{G}(1)$ and use that in (3.12) below than it is to solve (3.10) for $\mathcal{G}$ and use that in (3.9). Substitute (3.10) in the right-hand side of (3.9) to obtain

$$
\int_{0}^{1} \frac{\mathcal{G}(z)-1}{z} d z=\int_{0}^{1} \frac{\Phi(z \mathcal{G}(z))-1}{z} d z
$$

Now use the change of variable $t:=z \mathcal{G}(z)$. This gives us

$$
\begin{aligned}
\int_{0}^{1} \frac{\Phi(z \mathcal{G}(z))-1}{z} d z & =\int_{0}^{\mathcal{G}(1)} \frac{(\Phi(t)-1)\left(\Phi(t)-t \Phi^{\prime}(t)\right)}{t \Phi(t)} d t \\
& =\int_{0}^{\mathcal{G}(1)} \frac{\Phi(t)-1}{t} d t-\Phi(\mathcal{G}(1))+1+\log \Phi(\mathcal{G}(1)) \\
& =\int_{0}^{\mathcal{G}(1)} \frac{\Phi(t)-1}{t} d t-\mathcal{G}(1)+1+\log \mathcal{G}(1)
\end{aligned}
$$

Thus, we have

$$
\begin{equation*}
\mathbf{h}(G)=\log d-\int_{0}^{\mathcal{G}(1)} \frac{\Phi(t)-1}{t} d t+\mathcal{G}(1)-1-\log \mathcal{G}(1) . \tag{3.12}
\end{equation*}
$$

If we are interested only in the asymptotic complexity of finite graphs, for which $\rho$ would we want to calculate $\mathbf{h}(\rho)$ ? This is answered in Section 4 , where we shall see that all $\rho$ whose underlying graph is a fixed Cayley graph are included, among others.

Example 3.18. Suppose that $G$ is the free product $K_{s_{1}} * \cdots * K_{s_{n}}$ of the complete graphs $K_{s_{1}}, \ldots, K_{s_{n}}$ for some integers $s_{j} \geq 2$ with $\sum_{j} s_{j} \geq 5$. In other words, $G$ is the Cayley graph of the free product of groups of order $s_{j}$ with respect to the generating set corresponding to every element of the factors other than the identities. In order to calculate $\mathbf{h}(G)$, we shall find it easier to work with the graph $G^{\prime}$, in which we have added $n$ loops to each vertex of $G$. By Lemma 3.5, we have $\mathbf{h}\left(G^{\prime}\right)=\mathbf{h}(G)$. Let $d:=\sum_{j=1}^{n} s_{j}$ be the degree of $G^{\prime}$. Now by Woess (1984), we have

$$
\Phi_{G^{\prime}}(z)=1+\frac{z-n}{2}+\frac{1}{2} \sum_{j=1}^{n} \sqrt{\left(1-s_{j} z / d\right)^{2}+4 z / d}
$$

For example, if $n=2$, then (3.11) gives that $\mathcal{G}\left(1, G^{\prime}\right)=s_{1} s_{2} /\left(s_{1} s_{2}-s_{1}-s_{2}\right)$. We then find via (3.12) applied to $G^{\prime}$ that
$\mathbf{h}(G)=\left(1-\frac{1}{s_{1}}\right) \log \left(s_{1}-1\right)+\left(1-\frac{1}{s_{2}}\right) \log \left(s_{2}-1\right)+\left(1-\frac{1}{s_{1}}-\frac{1}{s_{2}}\right) \log \frac{s_{1}+s_{2}}{s_{1} s_{2}-s_{1}-s_{2}}$.
For example, if $s_{1}=2$ and $s_{2}=3$, when $G$ is a Cayley graph of the modular group $\operatorname{PSL}(2, \mathbb{Z})$ [use the generators $\left(\begin{array}{cc}0 & -1 \\ 1 & 0\end{array}\right)$ and $\left(\begin{array}{cc}0 & -1 \\ 1 & 1\end{array}\right)$ ], then $\mathbf{h}(G)=\log \left(2^{2 / 3} 5^{1 / 6}\right)$. As examples of other tree entropies that one may find by similar means, we mention that $\mathbf{h}(G)=\log (16 / 3)$ if $n=3$ with $s_{1}=s_{2}=s_{3}=3$, while

$$
\mathbf{h}(G)=\log (61+9 \sqrt{57})+\frac{1}{6} \log (317-33 \sqrt{57})-\frac{7}{2} \log 2-\log 7=1.190^{+}
$$

if $n=3$ with $s_{1}=s_{2}=2$ and $s_{3}=3$. As an application, suppose that $H_{n}$ is a random 3 -regular 3 -uniform hypergraph on $n$ vertices. Let $G_{n}$ be the associated graph in which every hyperedge of $H_{n}$ is replaced by a clique on its vertices. Then $G_{n}$ tends weakly to $K_{3} * K_{3} * K_{3}$, whence $n^{-1} \log \tau\left(G_{n}\right) \rightarrow \log (16 / 3)$.

Example 3.19. Choose a ray $\left\langle x_{m} ; m \geq 0\right\rangle$ in the regular tree $T$ of degree 3. Let $G_{m}$ be the ball in $T$ of radius $m$ about $x_{m}$. Remove the edge $\left[x_{m}, x_{m+1}\right.$ ] from $G_{m}$; let $T_{m}$ be the connected component of $x_{m}$ that remains. Thus, $T_{m} \subset T_{m+1}$ for all $m$. Let $G:=\bigcup_{m \geq 1} T_{m}$. The random weak limit of $\left\langle G_{m}\right\rangle$ is $\rho$, where $\rho\left(G, x_{m}\right):=2^{-m-1}$ for $m \geq 0$. Since $\tau\left(G_{m}\right)=1$, Theorem 3.3 tells us that $\mathbf{h}(\rho)=0$, i.e.,

$$
\sum_{k \geq 1} \frac{1}{k} \sum_{m \geq 0} 2^{-m-1} p_{k}\left(x_{m} ; G\right)=\log \sqrt{3}
$$

We comment finally on situations where the average degree of $\left\langle G_{n}\right\rangle$ is not bounded. We suspect that the following holds for "lazy" simple random walk $Q_{G}:=\left(I+P_{G}\right) / 2$ on any simple (unweighted) graph for some universal constant $C$ :

$$
\begin{equation*}
\forall k \geq 2 \quad|\mathrm{~V}(G)|^{-1}\left(\operatorname{tr} Q_{G}^{k}-1\right) \leq \frac{C}{\log ^{2} k} \tag{3.13}
\end{equation*}
$$

(It may even be true with $\log ^{2} k$ replaced by something like $k^{1 / 3}$, but as Ben Morris has pointed out, nothing better than $k^{1 / 3}$ is possible, as shown by the example of two cliques on $n$ vertices joined by a path of length $n$.) If (3.13) holds, this would replace Lemma 3.6 (except in the proof of Corollary 3.9) and allow results still more general than Theorem 3.3 for simple graphs.

As we have not been able to establish (3.13), we consider instead sequences $\left\langle G_{n}\right\rangle$ that are an expanding family, meaning that the second largest eigenvalue $\lambda_{2}\left(G_{n}\right)$ of $P_{G_{n}}$ is bounded away from 1. In this case, we do not need Lemma 3.6, since if $Q_{n}=Q_{G_{n}}$ is the transition matrix in the proof of Theorem 3.3, we have

$$
\left|\mathrm{V}\left(G_{n}\right)\right|^{-1}\left(\operatorname{tr} Q_{n}^{k}-1\right) \leq\left(\frac{1+\lambda_{2}\left(G_{n}\right)}{2}\right)^{k}
$$

for all $n, k \geq 1$. In addition, we do not need Lemma 3.5; that can be replaced with the corresponding statement for finite Markov chains,

$$
\sum_{k \geq 1}\left(\operatorname{tr} Q^{k}-1\right) / k=-\log (1-\alpha)+\sum_{k \geq 1}\left(\operatorname{tr} P^{k}-1\right) / k
$$

where $P$ and $Q$ are as in Lemma 3.5.

If the average degree of $\left\langle G_{n}\right\rangle$ is unbounded, we must consider a different normalization of the complexity. Let us assume that the limit (as $n \rightarrow \infty$ ) of the return probability after $k$ steps of simple random walk started at a random vertex of $G_{n}$ exists; denote it by $p_{k}$. For example, if $\left\langle G_{n}\right\rangle$ has a random weak limit $\rho$ that is concentrated on infinite graphs of finite degree, then $p_{k}=\int p_{k}(o ; G) d \rho(G, o)$. For another example, $p_{k}=0$ when $k \geq 1$ for simple graphs whose minimum degree tends to infinity. The proof of Theorem 3.3 (as modified above) shows that

$$
\lim _{n \rightarrow \infty}\left|\mathrm{~V}\left(G_{n}\right)\right|^{-1}\left[\log \tau\left(G_{n}\right)-\sum_{x \in \mathrm{~V}\left(G_{n}\right)} \log \operatorname{deg} x\right]=-\sum_{k \geq 1} p_{k} / k
$$

For a particular example, if $G_{n}$ is the giant component of the random graph $\mathcal{G}\left(n, p_{n}\right)$ with $n p_{n}-\log n \rightarrow \infty$ (which has $n$ vertices with probability tending to 1 ; see, e.g., Theorem 9 of Chapter VII in Bollobás (1998)), one has

$$
\lim _{n \rightarrow \infty}\left(n^{-1} \log \tau\left(G_{n}\right)-\log \left(p_{n} n\right)\right)=0
$$

in probability. To facilitate comparison to Cayley's theorem (that $\tau\left(K_{n}\right)=n^{n-2}$ ), we may state this as $\tau\left(G_{n}\right)=\left([1+o(1)] p_{n} n\right)^{n}$. (The fact that $\left\langle G_{n}\right\rangle$ is an expanding family a.s. is probably folklore. It can be proved as follows: First, the proof that $\mathcal{G}\left(n, p_{n}\right)$ is connected with probability approaching 1 is easily modified to show that its isoperimetric constant, also called conductance, is bounded away from 0 a.s. Second, a well-known inequality relating this constant to the second largest eigenvalue gives the result; see, e.g., Chung (1996).)

## §4. Tree Entropy as Log Determinant.

Under certain assumptions, Theorem 3.3 shows that if $\rho$ is a random weak limit of finite connected graphs, $G_{n}$, then its tree entropy $\mathbf{h}(\rho)$ is a limit of the logarithm of the determinant of the graph Laplacians of $G_{n}$, normalized by omitting the zero eigenvalue and by dividing by the number of vertices of $G_{n}$. In fact, one may give a formula for $\mathbf{h}(\rho)$ directly in terms of a normalized determinant of the graph Laplacian for infinite graphs. This is our main purpose in the present section. We shall also use this formula to prove inequalities for tree entropy and to calculate easily and quickly the classical tree entropy for Euclidean lattices.

We first discuss the class of probability measures $\rho$ to which our formula will apply. This class, the class of $\rho$ that arise as limits of finite graphs, is the class of unimodular $\rho$,
defined as follows. Given a rooted graph $(G, x)$ and an edge $e$ incident to $x$, define the involution $\iota(G, x, e):=(G, y, e)$, where $y$ is the other endpoint of $e$. Given a probability measure $\rho$ on rooted graphs, define the probability measure $\widehat{\rho}$ to be the law of the isomorphism class of $(G, x, e)$, where $(G, x)$ is chosen according to $\rho$ and $e$ is then chosen uniformly among the edges incident to $x$. Also, define $\widetilde{\rho}$ to be the (non-probability) measure that is the result of biasing $\widehat{\rho}$ by the degree of the root; that is, the Radon-Nikodým derivative of $\widetilde{\rho}$ with respect to $\widehat{\rho}$ at the isomorphism class of $(G, x, e)$ is $\operatorname{deg}_{G}(x)$. (If the expected degree of the root is finite, one could obtain a probability measure from $\widetilde{\rho}$ by dividing by the expected degree; but this is not always the case.) The involution $\iota$ induces a pushforward map $\widetilde{\rho} \mapsto \iota_{*} \widetilde{\rho}$. We say that $\rho$ is unimodular or involution invariant if $\iota_{*} \widetilde{\rho}=\widetilde{\rho}$. It is easy to see that any $\rho$ that is a random weak limit of finite graphs is unimodular, as observed by Aldous and Steele (2004), who introduced the notion of involution invariance; essentially the same observation occurs in Benjamini and Schramm (2001). The converse is much harder, but is established in Aldous and Lyons (2004). Intuitively, unimodularity means that, up to isomorphism, all vertices are equally likely to be the root. See Aldous and Lyons (2004) for a comprehensive treatment of unimodular random networks. In particular, it is shown there that a transitive graph is unimodular iff it is unimodular as a rooted random graph.

The preceding definitions and results extend easily to the class of rooted weighted graphs or multi-graphs $(G, o)$, where $G=(\mathrm{V}(G), \mathrm{E}(G), w)$ and $w: \mathrm{E}(G) \rightarrow[0, \infty)$ is a weight function as in Remark 3.11. For $x \neq y \in \mathrm{~V}(G)$, let $\Delta_{G}(x, y):=-\sum_{e} w(e)$, where the sum is over all the edges between $x$ and $y$, and $\Delta_{G}(x, x):=\sum_{e} w(e)$, where the sum is over all non-loop edges incident to $x$. We assume that $\Delta_{G}(x, x)<\infty$ for all $x$. The associated random walk has the transition probability from $x$ to $y$ of $-\Delta_{G}(x, y) / \Delta_{G}(x, x)$. Extend the definition of tree entropy to probability measures on rooted weighted graphs by

$$
\mathbf{h}(\rho):=\int\left(\log \Delta_{G}(o, o)-\sum_{k \geq 1} \frac{1}{k} p_{k}(o ; G)\right) d \rho(G, o)
$$

whenever this integral converges, where $p_{k}(o ; G)$ is the return probability after $k$ steps for the associated random walk.

The (graph) Laplacian $\Delta_{G}$ just defined determines an operator

$$
f \mapsto\left(x \mapsto \sum_{y \in \mathrm{~V}} \Delta_{G}(x, y) f(y)\right)
$$

for functions $f$ on V with finite support. This operator extends by continuity to a bounded linear operator on all of $\ell^{2}(\mathrm{~V})$ when $\sup _{x} \Delta_{G}(x, x)<\infty$. In case we do not have such a
uniform bound, we proceed as follows. Let $U_{e}$ be a uniform $[0,1]$-valued random variable chosen independently for all $e$. Given $M \in \mathbb{Z}^{+}$, let $G^{\prime}$ be the random weighted graph obtained from $G$ by letting the weight of $e$ be $w(e)\left(1-U_{e} / M\right)$. Now let $G_{M}$ be the weighted graph formed from $G^{\prime}$ by changing the weight to 0 of those edges $e$ whose weights are greater than $M$ or which are not among the $M$ largest weights of the edges incident to (or equal to) $e$. Clearly the matrix $\Delta_{G_{M}}$ converges to $\Delta_{G}$ entrywise a.s. as $M \rightarrow \infty$. Since $\Delta_{G_{M}}$ is a bounded self-adjoint positive semi-definite operator, the operator $\log \left(\Delta_{G_{M}}+\epsilon I\right)$ is bounded for any $\epsilon>0$, where $I$ denotes the identity operator on $\ell^{2}(\mathrm{~V})$. Let $\rho_{M}$ be the law of $\left(G_{M}, o\right)$ when $(G, o)$ has the law of $\rho$. If $\rho$ is unimodular, then so is $\rho_{M}$.

Now the logarithm of the determinant of a matrix equals the trace of the logarithm of the matrix. Furthermore, one usually defines the determinant via this equality when one has a trace on a von Neumann algebra. This is the approach we take.

The trace we use is defined by Aldous and Lyons (2004), which we review here. Suppose that $\rho$ is a unimodular probability measure on rooted weighted graphs. Let $T$ : $(G, o) \mapsto T_{G, o}$ be a measurable assignment of bounded linear operators $T_{G, o}: \ell^{2}(\mathrm{~V}(G)) \rightarrow$ $\ell^{2}(\mathrm{~V}(G))$ with finite supremum of the norms $\left\|T_{G, o}\right\|$. Let Alg be the von Neumann algebra of such operators $T$ that are equivariant in the sense that for all isomorphisms $\gamma: G_{1} \rightarrow G_{2}$ and all $o, x, y \in \mathrm{~V}(G)$, we have $\left(T_{G_{2}, \gamma o} \mathbf{1}_{\{\gamma x\}}, \mathbf{1}_{\{\gamma y\}}\right)=\left(T_{G_{1}, o} \mathbf{1}_{\{x\}}, \mathbf{1}_{\{y\}}\right)$. Since $T_{G, o}$ does not depend on $o \in G$ for $T \in \operatorname{Alg}$, we shall write $T_{G}$ in place of $T_{G, o}$ for $T \in \operatorname{Alg}$. We define the trace of $T \in \operatorname{Alg}$ to be

$$
\operatorname{Tr}(T):=\operatorname{Tr}_{\rho}(T):=\mathbf{E}\left[\left(T_{G} \mathbf{1}_{\{o\}}, \mathbf{1}_{\{o\}}\right)\right]:=\int\left(T_{G} \mathbf{1}_{\{o\}}, \mathbf{1}_{\{o\}}\right) d \rho(G, o)
$$

For self-adjoint operators $A$ and $B$, recall that $A \leq B$ means that $((B-A) v, v) \geq 0$ for all vectors $v$. Our trace has the following properties: $\operatorname{Tr}(\cdot)$ is linear, $\operatorname{Tr}(T) \geq 0$ for $T \geq 0$, and $\operatorname{Tr}(S T)=\operatorname{Tr}(T S)$ for $S, T \in$ Alg. In addition, for any increasing function $f: \mathbb{R} \rightarrow \mathbb{R}$ and any $S \leq T$, we have $\operatorname{Tr}(f(S)) \leq \operatorname{Tr}(f(T))$.

In effect, we now show the trace formula $\mathbf{h}(\rho)=\log \operatorname{Det}_{\rho} \Delta_{G}:=\operatorname{Tr}_{\rho}\left(\log \Delta_{G}\right)$. The determinant here is a so-called Fuglede-Kadison determinant; see Fuglede and Kadison (1952).

THEOREM 4.1. If $\rho$ is a unimodular probability measure on rooted infinite weighted graphs with

$$
\begin{equation*}
\int\left|\log \Delta_{G}(o, o)\right| d \rho(G, o)<\infty \tag{4.1}
\end{equation*}
$$

and

$$
\begin{equation*}
\int \frac{\Delta_{G}(o, o)}{\inf \left\{-\Delta_{G}(x, y) ; x \neq y \text { and } \Delta_{G}(x, y) \neq 0\right\}} d \rho(G, o)<\infty \tag{4.2}
\end{equation*}
$$

then

$$
\begin{equation*}
\mathbf{h}(\rho)=\lim _{M \rightarrow \infty} \lim _{\epsilon \downarrow 0} \operatorname{Tr}_{\rho}\left[\log \left(\Delta_{G_{M}}+\epsilon I\right)\right] . \tag{4.3}
\end{equation*}
$$

Proof. It is obvious that $\Delta_{G_{M}}+\epsilon I$ is monotone increasing in $\epsilon$. Furthermore, it is easy to check that $\Delta_{G_{M}}$ is monotone increasing in $M$. Since log is an increasing function, it follows that the limits exist in (4.3).

The condition (4.1) and Lebesgue's Dominated Convergence Theorem guarantee that

$$
\lim _{M \rightarrow \infty} \int \log \Delta_{G}(o, o) d \rho_{M}(G, o)=\int \log \Delta_{G}(o, o) d \rho(G, o)
$$

Clearly, for all $k>0$,

$$
\lim _{M \rightarrow \infty} \int p_{k}(o ; G) d \rho_{M}(G, o)=\int p_{k}(o ; G) d \rho(G, o)
$$

By Remark 3.7 and (4.2), it follows that

$$
\lim _{M \rightarrow \infty} \int \sum_{k \geq 1} \frac{1}{k} p_{k}(o ; G) d \rho_{M}(G, o)=\int \sum_{k \geq 1} \frac{1}{k} p_{k}(o ; G) d \rho(G, o)
$$

Therefore, we have

$$
\begin{equation*}
\lim _{M \rightarrow \infty} \mathbf{h}\left(\rho_{M}\right)=\mathbf{h}(\rho) \tag{4.4}
\end{equation*}
$$

Let $D_{G}$ be the diagonal matrix that has the same diagonal as $\Delta_{G}$. For $\epsilon>0$, define $P_{G, \epsilon}$ by

$$
\left(D_{G}+\epsilon I\right)\left(I-P_{G, \epsilon}\right)=\Delta_{G}+\epsilon I
$$

In other words, $P_{G, \epsilon}(x, x)=0$ and $P_{G, \epsilon}(x, y)=-\Delta_{G}(x, y) /\left(D_{G}(x, x)+\epsilon\right)$ for $x \neq y$. The matrix $P_{G, \epsilon}$ defines a killed random walk that, at $x$, is killed (sent to an absorbing cemetery state outside the graph $G$ ) with probability $\epsilon /\left(D_{G}(x, x)+\epsilon\right)$ and transits to $y$ with probability $P_{G, \epsilon}(x, y)$. Let $p_{k}(o ; G, \epsilon)$ be the return probability after $k$ steps for the killed random walk. It is clear that as $\epsilon \downarrow 0$, we have $p_{k}(o ; G, \epsilon) \uparrow p_{k}(o ; G)$. If the degrees of $G$ are bounded, then the norm of $P_{G, \epsilon}$ is less than 1 , whence

$$
\log \left(I-P_{G, \epsilon}\right)=-\sum_{k \geq 1} \frac{1}{k} P_{G, \epsilon}^{k}
$$

in particular,

$$
-\sum_{k \geq 1} \frac{1}{k} p_{k}(o ; G, \epsilon)=\left(\log \left(I-P_{G, \epsilon}\right) \mathbf{1}_{\{o\}}, \mathbf{1}_{\{o\}}\right)
$$

By a theorem of Fuglede and Kadison (1952), we have therefore for any $M$,

$$
\begin{aligned}
\mathbf{h}\left(\rho_{M}\right) & =\int\left(\log D_{G} \mathbf{1}_{\{o\}}, \mathbf{1}_{\{o\}}\right)-\sum_{k \geq 1} \frac{1}{k} p_{k}(o ; G) d \rho_{M}(G, o) \\
& =\lim _{\epsilon \downarrow 0} \int\left(\log \left(D_{G}+\epsilon I\right) \mathbf{1}_{\{o\}}, \mathbf{1}_{\{o\}}\right)-\sum_{k \geq 1} \frac{1}{k} p_{k}(o ; G, \epsilon) d \rho_{M}(G, o) \\
& =\lim _{\epsilon \downarrow 0} \int\left(\log \left(D_{G}+\epsilon I\right) \mathbf{1}_{\{o\}}, \mathbf{1}_{\{o\}}\right)+\left(\log \left(I-P_{G, \epsilon}\right) \mathbf{1}_{\{o\}}, \mathbf{1}_{\{o\}}\right) d \rho_{M}(G, o) \\
& =\lim _{\epsilon \downarrow 0} \operatorname{Tr}_{\rho_{M}}\left[\log \left(D_{G}+\epsilon I\right)+\log \left(I-P_{G, \epsilon}\right)\right] \\
& =\lim _{\epsilon \downarrow 0} \operatorname{Tr}_{\rho_{M}}\left[\log \left(\left(D_{G}+\epsilon I\right)\left(I-P_{G, \epsilon}\right)\right)\right] \\
& =\lim _{\epsilon \downarrow 0} \operatorname{Tr}_{\rho_{M}}\left[\log \left(\Delta_{G}+\epsilon I\right)\right] .
\end{aligned}
$$

Putting together this limit relation with that of (4.4), we obtain (4.3).
REmark 4.2. As $\Delta_{G}$ is unchanged by the addition or deletion of loops, we see that neither is $\mathbf{h}(\rho)$.

As one indication of the usefulness of Theorem 4.1 beyond its theoretical interest, we show how it leads immediately to calculation of the classically known tree entropy for the nearest-neighbor graph on $\mathbb{Z}^{d}$. In this case, the space $\ell^{2}\left(\mathbb{Z}^{d}\right)$ is isometrically isomorphic to $L^{2}\left([0,1]^{d}\right)$ (with Lebesgue measure) via the Fourier transform. Under this isomorphism, the Laplace operator $\Delta_{\mathbb{Z}^{d}}$ becomes the operator of multiplication by the function $\left(s_{1}, \ldots, s_{d}\right) \mapsto 2 d-2 \sum_{i=1}^{d} \cos \left(2 \pi s_{i}\right)$, the vector $\mathbf{1}_{\{o\}}$ becomes the constant function $\mathbf{1}$, and thus

$$
\mathbf{h}\left(\mathbb{Z}^{d}\right)=\int_{[0,1]^{d}} \log \left(2 d-2 \sum_{i=1}^{d} \cos \left(2 \pi s_{i}\right)\right) d s
$$

More generally, suppose that $G$ is a graph with vertex set $\mathbb{Z}^{d} \times K$ for a finite set $K$ and with edge set that is invariant under the natural action of $\mathbb{Z}^{d}$. That is, for each $x \in \mathbb{Z}^{d}$, there is an $K \times K$ matrix $L^{x}$ such that for $x, y \in \mathbb{Z}^{d}$ and $u, v \in K$,

$$
\Delta_{G}((x, u),(y, v))=L^{y-x}(u, v) .
$$

Such graphs $G$ are called "periodic" by Burton and Pemantle (1993). Consider the measure $\rho$ that puts equal mass on each $(G,(\mathbf{0}, u))(u \in K)$. We may regard $\Delta_{G}$ operating on $\ell^{2}\left(\mathbb{Z}^{d} \times K\right)$ as an operator $T$ on $\ell^{2}\left(\mathbb{Z}^{d} ; \ell^{2}(K)\right)$, that is, on the space of vector-valued functions $f: \mathbb{Z}^{d} \rightarrow \ell^{2}(K)$ with $\sum_{x \in \mathbb{Z}^{d}}\|f(x)\|_{\ell^{2}(K)}^{2}<\infty$. Under the Fourier isomorphism
with $L^{2}\left([0,1]^{d} ; \ell^{2}(K)\right)$, the operator $T$ becomes the operator of multiplication by the matrix-valued function

$$
M:\left(s_{1}, s_{2}, \ldots, s_{d}\right) \mapsto \sum_{x \in \mathbb{Z}^{d}} L^{x} e^{2 \pi i x \cdot s} \quad\left(s=\left(s_{1}, s_{2}, \ldots, s_{d}\right) \in[0,1]^{d}\right)
$$

the vector $\mathbf{1}_{\{(\mathbf{0}, u)\}}$ becomes the constant function $\mathbf{1}_{\{u\}} \in \ell^{2}(K)$, and thus

$$
\begin{aligned}
\mathbf{h}(\rho) & =|K|^{-1} \sum_{u \in K}\left(\left(\log \Delta_{G}\right) \mathbf{1}_{\{(\mathbf{0}, u)\}}, \mathbf{1}_{\{(\mathbf{0}, u)\}}\right) \\
& =|K|^{-1} \sum_{u \in K} \int_{[0,1]^{d}}\left((\log M(s)) \mathbf{1}_{\{u\}}, \mathbf{1}_{\{u\}}\right) d s \\
& =|K|^{-1} \int_{[0,1]^{d}} \operatorname{tr}(\log M(s)) d s \\
& =|K|^{-1} \int_{[0,1]^{d}} \log \operatorname{det} M(s) d s
\end{aligned}
$$

This is (a slightly simpler version of) the formula in Theorem 6.1(b) of Burton and Pemantle (1993).

We consider next some inequalities. If $\rho_{1}$ and $\rho_{2}$ are two probability measures on rooted weighted graphs, let us say that $\rho_{1}$ is edge dominated by $\rho_{2}$ if there exists a probability measure $\nu$ on rooted graphs $(G, o)$ with two sets of weights $\left(w_{1}, w_{2}\right)$ such that for all edges $e$, we have $w_{1}(e) \leq w_{2}(e)$ and such that the law of $\left(G, o, w_{i}\right)$ is $\rho_{i}$ for $i=1,2$. We call $\nu$ a monotone coupling of $\rho_{1}$ and $\rho_{2}$. When the weight of an edge is 0 , one can regard it as being absent.

THEOREM 4.3. If $\rho_{1} \neq \rho_{2}$ are unimodular probability measures on rooted weighted infinite loop-less graphs that both satisfy (4.1) and (4.2) and $\rho_{1}$ is edge dominated by $\rho_{2}$, then $\mathbf{h}\left(\rho_{1}\right)<\mathbf{h}\left(\rho_{2}\right)$.

The proof relies on the following notion. A continuous function $f:(0, \infty) \rightarrow \mathbb{R}$ is called operator monotone on $(0, \infty)$ if for any bounded self-adjoint operators $A, B$ with spectrum in $(0, \infty)$ and $A \leq B$, we have $f(A) \leq f(B)$. Löwner (1934) proved that the logarithm is an operator monotone function on $(0, \infty)$ (see also Chapter V of Bhatia (1997)).

Proof. As in the proof of Theorem 4.1, we have that $\Delta_{G_{M}, w_{1}} \leq \Delta_{G_{M}, w_{2}}$. Since log is an operator monotone function on $(0, \infty)$, it follows that $\operatorname{Tr}_{\rho_{1}}\left(\log \left(\Delta_{G_{M}, w_{1}}+\epsilon I\right)\right) \leq$ $\operatorname{Tr}_{\rho_{2}}\left(\log \left(\Delta_{G_{M}, w_{2}}+\epsilon I\right)\right)$, so that $\mathbf{h}\left(\rho_{1}\right) \leq \mathbf{h}\left(\rho_{2}\right)$ by Theorem 4.1. If $\mathbf{h}\left(\rho_{1}\right)=\mathbf{h}\left(\rho_{2}\right)$, then by Theorem 4.1, we have

$$
\lim _{M \rightarrow \infty} \lim _{\epsilon \downarrow 0}\left[\operatorname{Tr}_{\rho_{2}}\left(\log \left(\Delta_{G_{M}, w_{2}}+\epsilon I\right)\right)-\operatorname{Tr}_{\rho_{1}}\left(\log \left(\Delta_{G_{M}, w_{1}}+\epsilon I\right)\right)\right]=0
$$

Let $\nu$ be a monotone coupling of $\rho_{1}$ and $\rho_{2}$. Since log is an operator monotone function on $(0, \infty)$ with $\lim _{t \downarrow 0} t \log t=0$, we may apply a result from Aldous and Lyons (2004) to deduce that $\Delta_{G_{M}, w_{1}}=\Delta_{G_{M}, w_{2}} \nu$-a.s., i.e., that $\rho_{1}=\rho_{2}$.

REMARK 4.4. In case there is a unimodular monotone coupling $\nu$ (via marked graphs) of probability measures $\rho \neq \rho^{\prime}$ on rooted infinite graphs that have finite expected degree, where $\rho$ is edge dominated by $\rho^{\prime}$, then one can prove an explicit lower bound for the difference $\mathbf{h}\left(\rho^{\prime}\right)-\mathbf{h}(\rho)$. As shown in Aldous and Lyons (2004), there is then a sequence $\left\langle\left(G_{n}, G_{n}^{\prime}\right)\right\rangle$ of pairs of finite connected graphs on the same vertex sets and with the edge set of $G_{n}$ contained in the edge set of $G_{n}^{\prime}$ such that $G_{n}$ [resp., $G_{n}^{\prime}$ ] has a random weak limit $\rho$ [resp., $\rho^{\prime}$ ] with the average degree of $G_{n}^{\prime}$ tending to the $\rho^{\prime}$-expected degree of the root. A counting argument then shows that $\mathbf{h}\left(\rho^{\prime}\right)-\mathbf{h}(\rho) \geq c^{2}(\log 2) /\left[d(d+1)^{2}\right]$, where $c:=\nu\left[\left(G, G^{\prime}, o\right) ; \operatorname{deg}_{G^{\prime}}(o) \neq \operatorname{deg}_{G}(o)\right]$ and $d:=\overline{\operatorname{deg}}\left(\rho^{\prime}\right)$.

Corollary 3.9 shows that $\mathbf{h}(\rho)>-\infty$ as long as $\rho$ has finite expected degree. As an example where $\mathbf{h}(\rho)<0$, consider $\rho$ to be concentrated on the single rooted graph ( $\mathbb{N}, 0$ ). However, this is not possible in the unimodular case of unweighted graphs:

Proposition 4.5. If $\rho$ is a unimodular probability measure on rooted infinite (unweighted) graphs that has finite expected degree, then $\mathbf{h}(\rho) \geq 0$.

Proof. Under these hypotheses, Aldous and Lyons (2004) establish that $\rho$ is the random weak limit of a sequence of finite connected graphs with bounded average degree. Thus, we may apply Theorem 3.3.

Naturally, we wish to know when the tree entropy is 0 .
THEOREM 4.6. If $\rho$ is a unimodular probability measure on rooted infinite (unweighted) graphs that has finite expected degree, then $\mathbf{h}(\rho)=0$ iff $\overline{\operatorname{deg}}(\rho)=2$ iff $\rho$-a.s. $G$ is a locally finite tree with 1 or 2 ends.

Proof. The last equivalence is proved in Aldous and Lyons (2004). To prove the first equivalence, let $G_{n}$ be finite connected graphs whose random weak limit is $\rho$ and with bounded average degree. Let $T_{n}$ be a spanning tree of $G_{n}$. Since $\left\langle G_{n}\right\rangle$ is a tight sequence, so is $\left\langle T_{n}\right\rangle$. Therefore, by taking a subsequence if necessary, we may assume that $\left\langle T_{n}\right\rangle$ has a random weak limit $\rho_{0}$. Clearly, $\rho_{0}$ is edge dominated by $\rho$ and $\mathbf{h}\left(\rho_{0}\right)=0$ (since $\tau\left(T_{n}\right)=1$ ). Aldous and Lyons (2004) proved that $\overline{\operatorname{deg}}\left(\rho_{0}\right)=2$. Thus, $\overline{\operatorname{deg}}(\rho)=2$ iff $\rho=\rho_{0}$ iff $\mathbf{h}(\rho)=\mathbf{h}\left(\rho_{0}\right)$ by Theorem 4.3.

## §5. Metric Entropy.

Suppose that $G$ is an infinite quasi-transitive amenable connected graph. Choose one element $o_{i}$ from each vertex orbit. It is shown in BLPS (1999), Proposition 3.6, that there is a probability measure $\rho$ on the set $\left\{o_{i}\right\}$ such that for any Følner sequence $\left\langle H_{n}\right\rangle$, the relative frequency of vertices in $H_{n}$ that are in the same orbit as $o_{i}$ converges to $\rho\left(o_{i}\right)$. We call this measure $\rho$ the natural frequency distribution of $G$.

ThEOREM 5.1. Let $G$ be an infinite quasi-transitive amenable connected graph with natural frequency distribution $\rho$. Let $G_{n}$ be finite connected Følner subgraphs of $G$. Then

$$
\begin{equation*}
\lim _{n \rightarrow \infty} \frac{1}{\left|\mathrm{~V}\left(G_{n}\right)\right|} \log \tau\left(G_{n}\right)=\sum_{x \in \mathrm{~V}(G)} \rho(x) \log \operatorname{deg}_{G}(x)-\sum_{k \geq 1} \frac{1}{k} \sum_{x \in \mathrm{~V}(G)} \rho(x) p_{k}(x ; G)=\mathbf{h}(G, \rho) \tag{5.1}
\end{equation*}
$$

If $\Gamma \subseteq \operatorname{Aut}(G)$ is a countable finitely generated group acting freely on $\mathrm{V}(G)$ with a finite number I of orbits, then

$$
\begin{equation*}
\mathbf{H}\left(\mathrm{WSF}_{G}, \Gamma\right)=I \mathbf{h}(G, \rho) \tag{5.2}
\end{equation*}
$$

Furthermore, the $\Gamma$-entropy of any invariant measure on essential spanning forests of $G$ is at most $I \mathbf{h}(G, \rho)$.

We shall need several lemmas to prove Theorem 5.1.
Lemma 5.2. Let $G$ be an infinite quasi-transitive unimodular graph. If $G$ has 2 ends, then $\mathfrak{F}$ is a tree with exactly 2 ends WSF-a.s., while otherwise, for WSF-a.e. $\mathfrak{F}$, each component tree of $\mathfrak{F}$ has exactly one end.

Proof. Pemantle (1991) established this one-endedness for $G=\mathbb{Z}^{d}$ when $2 \leq d \leq 4$. BLPS (2001) proved this in the general case that $G$ is transitive (and unimodular). This latter proof is long, but not too hard to modify so as to apply to quasi-transitive graphs. The case where $G$ has 2 ends or is recurrent needs only a few simple modifications that we do not detail. The major changes needed in the transient case with other than 2 ends are as follows. Let $\left\{o_{i}\right\}$ be a set of representatives of the orbits of V and let $w_{i}$ be the reciprocal of the Haar measure of the stabilizer of $o_{i}$, where we normalize Haar measure so that $\sum_{i} w_{i}=1$. (In the amenable case, we have $w_{i}=\rho\left(o_{i}\right)$ by BLPS (1999), Proposition 3.6.) Consider any $\operatorname{Aut}(G)$-invariant probability measure $\mathbf{P}$ on $2^{\mathrm{E}(G)}$. For any subgraph $\omega$ of $G$ and any vertex $x$, write $D(x)$ for the degree of $x$ in $\omega$. Let $A_{i}$ be the event that the component of $o_{i}$ in $\omega$ is infinite and $p_{\infty, i}:=\mathbf{P}\left[A_{i}\right]$. Then according to Theorem 6.4 of BLPS (1999), we have

$$
\begin{equation*}
\sum_{i} w_{i} \mathbf{E}\left[D\left(o_{i}\right) ; A_{i}\right] \geq \sum_{i} 2 w_{i} p_{\infty, i} \tag{5.3}
\end{equation*}
$$

We may use this to prove an analogue of Theorem 7.2 in BLPS (1999), namely, that if some component of $\omega$ has at least 3 ends with positive probability, then strict inequality holds in (5.3). The next step is to combine the proof of Theorem 6.5 of BLPS (2001) with Corollary 3.5 of BLPS (1999) to show that when $\mathbf{P}=\mathrm{WSF}_{G}$, we have $\sum_{i} w_{i} \mathbf{E}\left[D\left(o_{i}\right)\right]=2$, so that equality holds in (5.3). Therefore, each tree has at most 2 ends WSF-a.s. The rest of the proof needs simple obvious modifications only, except for the crucial "trunk" lemma, i.e., Lemma 10.5 of BLPS (2001). Almost all of this proof can also be used word for word. The only significant change needed is that if $o_{i}$ is on the trunk, then the shift along the trunk should bring to $o_{i}$ the next vertex in the orbit of $o_{i}$ in the direction of the orientation of the trunk.

For our other lemmas, we shall find the following notation convenient. Given a finite subgraph $H$ of a graph $G$ and a configuration $\omega$ of $\mathrm{E}(G)$, let $H(\omega)$ denote the cylinder event consisting of those configurations of $\mathrm{E}(G)$ that agree with $\omega$ on $\mathrm{E}(H)$. Given also a configuration $\omega$ of $\mathrm{E}(G) \backslash \mathrm{E}(H)$, we define two finite graphs from certain vertex identifications on $H$ : Write $H \circ \omega$ for the graph obtained by identifying all vertices of $H$ that are connected to each other in the graph $(\mathrm{V}(G), \omega)$. Write $H * \omega$ for the graph obtained by identifying all vertices of $H$ that are connected to each other in the graph $(\mathrm{V}(G), \omega)$ and by identifying all vertices of $H$ that belong to any infinite connected component in $(\mathrm{V}(G), \omega)$. Note that in $H * \omega$, each finite component of $(\mathrm{V}(G), \omega)$ yields a separate identification, while the infinite components of $(\mathrm{V}(G), \omega)$ yield together one single identification.

The next lemma provides another justification for the adjective "uniform" in "wired uniform spanning forest", similar to a Gibbs specification. However, it does not hold for all graphs.

Lemma 5.3. Let $G$ be an infinite quasi-transitive unimodular graph and let $H$ be a finite connected subgraph of $G$. If $G$ has 2 ends, then

$$
\operatorname{WSF}(H(\mathfrak{F}) \mid \mathfrak{F} \upharpoonright(\mathrm{E} \backslash \mathrm{E}(H)))=\tau(H \circ(\mathfrak{F} \upharpoonright(\mathrm{E} \backslash \mathrm{E}(H))))^{-1} \quad \text { WSF-a.s., }
$$

while otherwise,

$$
\operatorname{WSF}(H(\mathfrak{F}) \mid \mathfrak{F} \upharpoonright(\mathrm{E} \backslash \mathrm{E}(H)))=\tau(H *(\mathfrak{F} \upharpoonright(\mathrm{E} \backslash \mathrm{E}(H))))^{-1} \quad \text { WSF-a.s. }
$$

Proof. The case where $G$ has 2 ends is similar, though simpler, than the other case, so we give the details only for the case where $G$ has other than 2 ends. Let $Z$ be the event that each tree of $\mathfrak{F}$ has exactly one end. By Lemma 5.2, we have $\operatorname{WSF}(Z)=1$.

Let $B_{R}$ denote the ball of radius $R$ about some fixed vertex of $G$. Choose $R_{H}$ so that $H \subset B_{R_{H}}$. Let $A_{R}$ be the event that for all $x, y \in \partial_{V} H$ and $z, w \in \partial_{V} B_{R}$, if in $\mathfrak{F} \upharpoonright\left(\mathrm{E}\left(B_{R}\right) \backslash \mathrm{E}(H)\right)$

- $x$ is connected to $z$,
- $y$ is connected to $w$, and
- $x$ is not connected to $w$,
then $x$ and $y$ are not connected in $\mathfrak{F} \upharpoonright \mathrm{E}(H)$. Thus, $A_{R} \subseteq A_{R+1}$ for all $R \geq R_{H}$ and

$$
Z \subseteq \bigcup_{R} A_{R}
$$

whence $\lim _{R \rightarrow \infty} \operatorname{WSF}\left(A_{R}\right)=1$. Since

$$
\operatorname{WSF}\left(A_{R}\right)=\int \operatorname{WSF}\left(A_{R} \mid \mathfrak{F} \upharpoonright\left(\mathrm{E}\left(B_{R}\right) \backslash \mathrm{E}(H)\right)\right) d \mathrm{WSF}
$$

it follows that for all large $R$, we have

$$
\operatorname{WSF}\left(C_{R}\right) \geq 1-\sqrt{1-\operatorname{WSF}\left(A_{R}\right)}
$$

where

$$
C_{R}:=\left\{\mathfrak{F} ; \operatorname{WSF}\left(A_{R} \mid \mathfrak{F} \upharpoonright\left(\mathrm{E}\left(B_{R}\right) \backslash \mathrm{E}(H)\right)\right) \geq 1-\sqrt{1-\operatorname{WSF}\left(A_{R}\right)}\right\} .
$$

In particular, WSF $\left(\limsup \operatorname{sum}_{R \rightarrow \infty} C_{R}\right)=1$.
By definition,

$$
\operatorname{WSF}(H(\mathfrak{F}) \mid \mathfrak{F} \upharpoonright(\mathrm{E} \backslash \mathrm{E}(H)))=\lim _{R \rightarrow \infty} \operatorname{WSF}\left(H(\mathfrak{F}) \mid \mathfrak{F} \upharpoonright\left(\mathrm{E}\left(B_{R}\right) \backslash \mathrm{E}(H)\right)\right) \quad \text { WSF-a.s. }
$$

Fix a forest $\omega \in Z \cap \lim \sup _{R \rightarrow \infty} C_{R}$ for which the limit above holds. Choose $\epsilon>0$ arbitrarily small. Choose $R \geq R_{H}$ so large that

$$
\begin{equation*}
\left|\operatorname{WSF}(H(\omega) \mid \omega \upharpoonright(\mathrm{E} \backslash \mathrm{E}(H)))-\operatorname{WSF}\left(H(\omega) \mid \omega \upharpoonright\left(\mathrm{E}\left(B_{R}\right) \backslash \mathrm{E}(H)\right)\right)\right|<\epsilon \tag{5.4}
\end{equation*}
$$

that $\omega \in C_{R}$, that $\sqrt{1-\operatorname{WSF}\left(A_{R}\right)}<\epsilon$, and that each vertex in $\partial_{\vee} H$ that is connected in $\omega \upharpoonright\left(\mathrm{E}\left(B_{R}\right) \backslash \mathrm{E}(H)\right)$ to $\partial_{\mathrm{V}} B_{R}$ belongs to an infinite component in $\omega \upharpoonright(\mathrm{E} \backslash \mathrm{E}(H))$. This last requirement, in combination with $\omega \in Z$, implies that $\omega \in A_{R}$. Consider the cylinder set

$$
D:=\left(B_{R} \backslash \mathrm{E}(H)\right)(\omega)=\left\{\mathfrak{F} ; \mathfrak{F} \upharpoonright\left(\mathrm{E}\left(B_{R}\right) \backslash \mathrm{E}(H)\right)=\omega \upharpoonright\left(\mathrm{E}\left(B_{R}\right) \backslash \mathrm{E}(H)\right)\right\}
$$

Let $\mu_{N}$ be the uniform spanning tree measure on $B_{N}^{*}$. By definition,

$$
\operatorname{WSF}(H(\omega) \mid D)=\lim _{N \rightarrow \infty} \mu_{N}(H(\omega) \mid D)
$$

and

$$
\operatorname{WSF}\left(A_{R} \mid D\right)=\lim _{N \rightarrow \infty} \mu_{N}\left(A_{R} \mid D\right)
$$

Since $\omega \in C_{R}$ and $\sqrt{1-\operatorname{WSF}\left(A_{R}\right)}<\epsilon$, we have $\operatorname{WSF}\left(A_{R} \mid D\right)>1-\epsilon$. Thus, we may choose $N>R$ so large that

$$
\left|\operatorname{WSF}(H(\omega) \mid D)-\mu_{N}(H(\omega) \mid D)\right|<\epsilon
$$

and $\mu_{N}\left(A_{R} \mid D\right)>1-\epsilon$. Since

$$
\mu_{N}(H(\omega) \mid D)=\mu_{N}\left(A_{R} \mid D\right) \mu_{N}\left(H(\omega) \mid A_{R} \cap D\right)+\mu_{N}\left(A_{R}^{c} \mid D\right) \mu_{N}\left(H(\omega) \mid A_{R}^{c} \cap D\right),
$$

we have

$$
\left|\mu_{N}(H(\omega) \mid D)-\mu_{N}\left(H(\omega) \mid A_{R} \cap D\right)\right|<2 \epsilon
$$

Given $A_{R} \cap D$, the configurations inside $H$ and outside $B_{R}$ are $\mu_{N}$-independent. Since $\omega \in A_{R}$, it follows that

$$
\mu_{N}\left(H(\omega) \mid A_{R} \cap D\right)=\tau(H * \omega)^{-1}
$$

and so

$$
\left|\operatorname{WSF}(H(\omega) \mid D)-\tau(H * \omega)^{-1}\right|<3 \epsilon .
$$

Therefore,

$$
\left|\operatorname{WSF}(H(\omega) \mid \omega \upharpoonright(\mathrm{E} \backslash \mathrm{E}(H)))-\tau(H * \omega)^{-1}\right|<4 \epsilon
$$

by (5.4). Since $\epsilon$ is arbitrary and $\omega$ is an arbitrary element of a set of measure 1 , the result follows.

Lemma 5.4. Let $H$ be a finite connected graph and $W$ be a subset of vertices of $H$. Let $H^{\prime}$ be any graph obtained from $H$ by making certain identifications of the vertices in $W$ with each other. Write $\alpha:=(|W|-1) /|\mathrm{E}(H)|$. Then

$$
\left|\log \tau(H)-\log \tau\left(H^{\prime}\right)\right| \leq|\mathrm{E}(H)|(-\alpha \log \alpha-(1-\alpha) \log (1-\alpha))
$$

Proof. Let $\mu$ be the uniform spanning tree measure on $H$ and $\mu^{\prime}$ the uniform spanning tree measure on $H^{\prime}$. It follows from Feder and Mihail (1992) that $\mu$ stochastically dominates $\mu^{\prime}$. By Strassen's (1965) theorem, this means that there is a probability measure on pairs $\left(T, T^{\prime}\right)$ so that the law of $T$ is $\mu$, the law of $T^{\prime}$ is $\mu^{\prime}$, and $T \supseteq T^{\prime}$ a.s. Now $|\mathrm{E}(T)|=|\mathrm{V}(H)|-1$ and $\left|\mathrm{E}\left(T^{\prime}\right)\right|=\left|\mathrm{V}\left(H^{\prime}\right)\right|-1$. We deduce that a.s.

$$
\left|\mathrm{E}(T) \triangle \mathrm{E}\left(T^{\prime}\right)\right|=|\mathrm{V}(H)|-\left|\mathrm{V}\left(H^{\prime}\right)\right| \leq|W|-1
$$

It now follows from Lemma 2.1 that

$$
\left|\mathbf{H}(\mu)-\mathbf{H}\left(\mu^{\prime}\right)\right| \leq|\mathbf{E}(H)|(-\alpha \log \alpha-(1-\alpha) \log (1-\alpha)) .
$$

Since $\mathbf{H}(\mu)=\log \tau(H)$ and $\mathbf{H}\left(\mu^{\prime}\right)=\log \tau\left(H^{\prime}\right)$, this is the same as the desired inequality.

Lemma 5.5. Let $G$ be an infinite quasi-transitive unimodular graph and $H$ be a finite connected subgraph of $G$. Write $\alpha:=\left(\left|\partial_{\mathrm{V}} H\right|-1\right) /|\mathrm{E}(H)|$. Then for WSF-a.e. $\mathfrak{F}$,

$$
\left|\log \operatorname{WSF}(H(\mathfrak{F}))-\log \tau(H)^{-1}\right| \leq|\mathbf{E}(H)|(-\alpha \log \alpha-(1-\alpha) \log (1-\alpha))
$$

Proof. Write $\beta:=\alpha^{-\alpha}(1-\alpha)^{-(1-\alpha)}$. According to Lemma 5.4, we have $\tau\left(H^{\prime}\right)^{-1} \in I_{H}$, where

$$
I_{H}:=\left[\tau(H)^{-1} \beta^{-|\mathbf{E}(H)|}, \tau(H)^{-1} \beta^{|\mathbf{E}(H)|}\right]
$$

and $H^{\prime}:=H \circ(\mathfrak{F} \upharpoonright(\mathrm{E} \backslash \mathrm{E}(H)))$ if $G$ has 2 ends, while $H^{\prime}:=H *(\mathfrak{F} \upharpoonright(\mathrm{E} \backslash \mathrm{E}(H)))$ otherwise. Combining the preceding relation with Lemma 5.3, we obtain

$$
\operatorname{WSF}(H(\mathfrak{F}))=\mathbf{E}[\operatorname{WSF}(H(\mathfrak{F}) \mid \mathfrak{F} \upharpoonright(\mathrm{E} \backslash \mathrm{E}(H)))] \in I_{H}
$$

a.s. This is the same as the desired inequality.

Lemma 5.6. Let $H$ be a finite connected graph and $W$ be a subset of vertices of $H$. Let $\tau_{\mathrm{e}}(H, W)$ be the number of spanning forests of $H$ such that each tree contains at least one vertex of $W$. Write $\alpha:=(|W|-1) /|\mathrm{E}(H)|$. Then

$$
\log \tau_{\mathrm{e}}(H, W) \leq \log \tau(H)+|\mathrm{E}(H)|(-\alpha \log \alpha-(1-\alpha) \log (1-\alpha))
$$

Proof. Let $\mu$ be the uniform measure on spanning forests of $H$ such that each tree contains at least one vertex of $W$. Let $\nu$ be obtained from $\mu$ by choosing a spanning forest $\mathfrak{F}$ with distribution $\mu$ and then randomly adding to $\mathfrak{F}$ enough edges of $H$ so that a spanning tree of $H$ results. By Lemma 2.1, we have

$$
|\mathbf{H}(\mu)-\mathbf{H}(\nu)| \leq|\mathrm{E}(H)|(-\alpha \log \alpha-(1-\alpha) \log (1-\alpha))
$$

since at most $|W|-1$ edges are added. Since $\mathbf{H}(\mu)=\log \tau_{\mathrm{e}}(H, W)$ and $\mathbf{H}(\nu) \leq \log \tau(H)$, the desired inequality follows.

Proof of Theorem 5.1. We first prove that (5.1) holds. By definition of $\rho$, the graphs $G_{n}$ have a random weak limit $(G, \rho)$. Thus, [5.1] is a consequence of Theorem 3.3.

We next show (5.2). Choose a ball $B_{R}(o)$ of vertices and edges such that $\Gamma B_{R}(o)=G$. Let

$$
\Gamma_{n}:=\left\{\gamma \in \Gamma ; \gamma B_{R}(o) \cap G_{n} \neq \varnothing\right\}
$$

and put

$$
G_{n}^{\prime}:=\Gamma_{n} B_{R}(o) .
$$

Since $\left\langle G_{n}\right\rangle$ is a Følner sequence in $G$, it follows that $\left\langle\Gamma_{n}\right\rangle$ is a Følner sequence in $\Gamma$. Therefore,

$$
\mathbf{H}(\mathrm{WSF}, \Gamma)=-\lim _{n \rightarrow \infty}\left|\Gamma_{n}\right|^{-1} \log \operatorname{WSF}\left(G_{n}^{\prime}(\mathfrak{F})\right)
$$

in $L^{1}$ (WSF) by the generalized Shannon-McMillan Theorem of Kieffer (1975). Now

$$
\lim _{n \rightarrow \infty}\left|\mathrm{~V}\left(G_{n}^{\prime}\right)\right| /\left|\Gamma_{n}\right|=I
$$

since $\Gamma$ acts freely on V. Hence

$$
\begin{equation*}
\mathbf{H}(\mathrm{WSF}, \Gamma)=-\lim _{n \rightarrow \infty} I\left|\mathrm{~V}\left(G_{n}^{\prime}\right)\right|^{-1} \log \operatorname{WSF}\left(G_{n}^{\prime}(\mathfrak{F})\right) \tag{5.5}
\end{equation*}
$$

in $L^{1}$ (WSF). As we recalled in Section 2, every quasi-transitive amenable graph is unimodular. The result now follows from Lemma 5.5 in conjunction with 5.5 .

We finally show that no measure $\mu$ on essential spanning forests of $G$ has larger entropy. Using some of the same reasoning as above, we have that

$$
\mathbf{H}(\mu, \Gamma)=\lim _{n \rightarrow \infty}\left|\Gamma_{n}\right|^{-1} \mathbf{H}\left(\mu \mid G_{n}^{\prime}\right)
$$

Because $\mu$ is concentrated on essential spanning forests, the number of elements of the partition generated by $G_{n}^{\prime}$ that have positive $\mu$-measure is at most $\tau_{\mathrm{e}}\left(G_{n}^{\prime}, \partial_{\mathrm{V}} G_{n}^{\prime}\right)$, whence $\mathbf{H}\left(\mu \upharpoonright G_{n}^{\prime}\right) \leq \log \tau_{\mathrm{e}}\left(G_{n}^{\prime}, \partial_{\mathrm{V}} G_{n}^{\prime}\right)$. We may apply Lemma 5.6 to obtain the desired conclusion.

Acknowledgements. I am grateful to Wolfgang Woess, Thierry Coulhon, Ben Morris, Yuval Peres, and Scott Sheffield for useful discussions and references. Thanks are due to Benny Sudakov for asking about the asymptotics for graphs whose degree tends to infinity.

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[^0]:    2000 Mathematics Subject Classification. Primary 05C05, 60C05. Secondary 60K99, 05C80, 82B20, 28D05, 37A05.
    Key words and phrases. Asymptotic complexity, graphs, domino tilings, tree entropy, random walks, metric entropy, uniform spanning forests, determinant, Laplacian, trace.
    Research partially supported by NSF grants DMS-0103897 and DMS-0231224.
    1 It appears not to have been noticed before that in the case of Euclidean lattice graphs, one can dispense with eigenvalues and go directly to the limit by invoking Szegó's limit theorem. In one dimension, this theorem appears in, e.g., Grenander and Szegő (1984), p. 44. In higher dimensions, it is due to Helson and Lowdenslager (1958), but the form in which they present it does not involve determinants. See the last part of the proof of Theorem 5.11 in Lyons and Steif (2003) to see how to transform their result to give the asymptotics of determinants. In any case, use of our formula is simpler still.

[^1]:    2 Another possible name, "combinatorial entropy", is already in use with a variety of meanings.

[^2]:    ${ }^{3}$ In the $\mathbb{Z}^{d}$-transitive case, it is not hard to pass directly between our series representation and the standard integral representation.

[^3]:    ${ }^{4}$ By a "spanning forest", we mean a subgraph without cycles that contains every vertex.

