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LIMITS OF STRUCTURES AND THE EXAMPLE OF TREE-SEMILATTICES

PIERRE CHARBIT, LUCAS HOSSEINI, AND PATRICE OSSONA DE MENDEZ

ABSTRACT. The notion of left convergent sequences of graphs introduced by Lovász et al. (in relation with homomorphism densities for fixed patterns and Szemerédi’s regularity lemma) got increasingly studied over the past 10 years. Recently, Nešetřil and Ossona de Mendez introduced a general framework for convergence of sequences of structures. In particular, the authors introduced the notion of QF -convergence, which is a natural generalization of left-convergence. In this paper, we initiate study of QF -convergence for structures with functional symbols by focusing on the particular case of tree semi-lattices. We fully characterize the limit objects and give an application to the study of left convergence of m -partite cographs, a generalization of cographs.

1. INTRODUCTION

The study of limits of graphs gained recently a major interest [5, 6, 9, 22, 23, 24]. In the framework studied in the aforementioned papers, a sequence $(G_n)_{n \in \mathbb{N}}$ of graphs is said *left-convergent* if, for every (finite) graph F , the probability

$$t(F, G_n) = \frac{\text{hom}(F, G_n)}{|G_n|^{|F|}}$$

that a random map $f : V(F) \rightarrow V(G_n)$ is a *homomorphism* (i.e. a mapping preserving adjacency) converges as n goes to infinity. (For a graph G , we denote by $|G|$ the *order* of G , that is the number of vertices of G .) In this case, the limit object can be represented by means of a *graphon*, that is a measurable function $W : [0, 1]^2 \rightarrow [0, 1]$. The definition of the function t above is extended to graphons by

$$t(F, W) = \int \cdots \int \prod_{ij \in E(F)} W(x_i, x_j) \, dx_1 \dots dx_p$$

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(where we assume that F is a graph with vertex set $\{1, \dots, p\}$) and then the graphon W is the left-limit of a left-convergent sequence of graphs $(G_n)_{n \in \mathbb{N}}$ if for every graph F it holds

$$t(F, W) = \lim_{n \rightarrow \infty} t(F, G_n).$$

For k -regular hypergraphs, the notion of left-convergence extends in the natural way, and left-limits — called *hypergraphons* — are measurable functions $W : [0, 1]^{2^k-2} \rightarrow [0, 1]$ and have been constructed by Elek and Szegedy using ultraproducts [10] (see also [28]). These limits were also studied by Hoover [15], Aldous [1], and Kallenberg [21] in the setting of exchangeable random arrays (see also [3]). For other structures, let us mention limits of permutations [17, 16] and limits of posets [7, 19, 14].

A *signature* σ is a set of symbols of relations and functions with their arities. A σ -structure \mathbf{A} is defined by its *domain* A and an interpretation in A of all the relations and functions declared in σ . A σ -structure is *relational* if the signature σ only contains symbols of relations. Thus relational structures are natural generalization of k -uniform hypergraphs. To the opposite, a σ -structure is *functional* (or called an *algebra*) if the signature σ only contains symbols of functions. Denote by $\text{QF}_p(\sigma)$ the fragment of all quantifier free formulas with p free variables (in the language of σ) and by $\text{QF}(\sigma) = \bigcup_p \text{QF}_p(\sigma)$ the fragment of all quantifier free formulas. In the following, we shall use QF_p and QF when the signature σ is clear from context. For a formula ϕ with p free variables, the set of satisfying assignments of ϕ is denoted by $\phi(\mathbf{A})$:

$$\phi(\mathbf{A}) = \{(v_1, \dots, v_p) \in A^p : \mathbf{A} \models \phi(v_1, \dots, v_p)\}$$

In the general framework of finite σ -structures (that is a σ -structure with finite domain), the notion of *QF-convergence* has been introduced by Nešetřil and the third author [26]. In this setting, a sequence $(\mathbf{A}_n)_{n \in \mathbb{N}}$ of σ -structures is *QF-convergent* if, for every quantifier free formula ϕ with free variables x_1, \dots, x_p , the probability

$$(1) \quad \langle \phi, \mathbf{A}_n \rangle = \frac{|\phi(\mathbf{A}_n)|}{|A_n|^p}$$

that a random (uniform independent) assignment to the free variables of ϕ of elements of A_n satisfies ϕ converges as n goes to infinity. These notions naturally extends to *weighted structures*, that is structures equipped with a non uniform probability measure.

The notion of QF-convergence extends several notions of convergence.

It was proven in [26] that a sequence of graphs (or of k -uniform hypergraphs) with order going to infinity is QF-convergent if and only if it is left-convergent. This is intuitive, as for every finite graph F with vertex set $\{1, \dots, p\}$ there is a quantifier-free formula ϕ_F with free variable x_1, \dots, x_p such that for every graph G and every p -tuple (v_1, \dots, v_p) of vertices of G it

holds $G \models \phi_F(v_1, \dots, v_p)$ if and only if the map $i \mapsto v_i$ is a homomorphism from F to G .

As mentioned before the left-limit of a left-convergent sequence of graphs can be represented by a graphon. However it cannot, in general, be represented by a Borel graph — that is a graph having a standard Borel space V as its vertex set and a Borel subset of $V \times V$ as its edge set. A graphon W is *random-free* if it is almost everywhere $\{0, 1\}$ -valued. Notice that a random-free graphon is essentially the same (up to isomorphism mod 0) as a Borel graph equipped with a non-atomic probability measure on V . A class of graph \mathcal{C} is said to be *random-free* if, for every left-convergent sequence of graphs $(G_n)_{n \in \mathbb{N}}$ with $G_n \in \mathcal{C}$ (for all n) the sequence $(G_n)_{n \in \mathbb{N}}$ has a random-free limit.

Local convergence of graphs with bounded degree has been defined by Benjamini and Schramm [4]. A sequence $(G_n)_{n \in \mathbb{N}}$ of graphs with maximum degree D is *local-convergent* if, for every $r \in \mathbb{N}$, the distribution of the isomorphism types of the distance r -neighborhood of a random vertex of G_n converges as n goes to infinity. This notion can also be expressed by means of QF-convergence (in a slightly stronger form). Let G_1, \dots, G_n, \dots be graphs with maximum degree strictly smaller than D . By considering a proper edge coloring of G_n by D colors, we can represent G_n as a functional structure \mathbf{V}_n with signature containing D unary functions f_1, \dots, f_D , where V_n is the vertex set of G_n and f_i, \dots, f_D are defined as follows: for every vertex $v \in V_n$, $f_i(v)$ is either the unique vertex adjacent to v by an edge of color i , or v if no edge of color i is incident to v . It is easily checked that if the sequence $(\mathbf{V}_n)_{n \in \mathbb{N}}$ is QF-convergent if and only if the sequence $(G_n)_{n \in \mathbb{N}}$ of edge-colored graphs is local-convergent. If $(\mathbf{V}_n)_{n \in \mathbb{N}}$ is QF-convergent, then the limit is a *graphing*, that is a functional structure \mathbf{V} (with same signature as \mathbf{V}_n) such that V is a standard Borel space, and f_1, \dots, f_D are measure-preserving involutions.

In the case above, the property of the functions to be involutions is essential. The case of quantifier free limits of general functional structures is open, even in the case of unary functions. Only the simplest case of a single unary function has been recently settled [27]. The case of QF-limits of functional structures with a single binary function is obviously at least as complicated as the case of graphs, as a graph G can be encoded by means of a (non-symmetric) function f defined by $f(u, v) = u$ if u and v are adjacent, and $f(u, v) = v$ otherwise, with the property that QF-convergence of the encoding is equivalent to left-convergence of the graphs. The natural guess here for a limit object is the following:

Conjecture 1. *Let σ be the signature formed by a single binary functional symbol f .*

Then the limit of a QF-convergent sequence of finite σ -structures can be represented by means of a measurable function $w : [0, 1] \times [0, 1] \rightarrow \mathfrak{P}([0, 1])$, where $\mathfrak{P}([0, 1])$ stands for the space of probability measures on $[0, 1]$.

As witnessed by the case of local-convergence of graphs with bounded degrees, the “random-free” case, that is the case where the limit object can be represented by a Borel structure with same signature, is of particular interest. In this paper, we will focus on the case of simple structures defined by a single binary function — the tree semi-lattices — and we will prove that they admit Borel tree semi-lattices for QF-limits. Conversely, we will prove that every Borel tree semi-lattices (with domain equipped with an atomless probability measure) can be arbitrarily well approximated by a finite tree semi-lattices, hence leading to a full characterization of QF-limits of finite tree semi-lattices.

2. STATEMENT OF THE RESULTS

A *tree-semilattice* is an algebraic structure $\mathbf{T} = (T, \wedge)$ such that:

- (1) (T, \wedge) is a meet semi-lattice (i.e. an idempotent commutative semi-group);
- (2) $\forall x, y, z$ s.t. $x \wedge z = x$ and $y \wedge z = y$ it holds $x \wedge y \in \{x, y\}$.

Because we consider structures with infimum operator \wedge , note that we shall use the symbol $\&$ for the logical conjunction.

Each tree-semilattice \mathbf{T} canonically defines a partial order on its domain by $x \leq y$ if $x \wedge y = x$. In the case where T is finite, it is a partial order induced by the ancestor relation of a rooted tree.

It is possible to add finitely many unary relations M_1, \dots, M_k to the signature of tree-semilattices. In this case, we speak of *colored* tree-semilattices, and we define the color of a vertex v as the set of the indices of those unary relations it belongs to: $c(v) = \{i : M_i(v)\}$.

A *Borel tree-semilattice* is a tree-semilattice \mathbf{T} on a standard Borel space T , such that $\wedge : T \times T \rightarrow T$ is Borel. Note that every finite tree-semilattice is indeed a Borel tree-semilattice.

Our main results concerning QF-convergence of tree-semilattices are as follows:

- every QF-convergent sequence of finite colored weighted tree-semilattices admits a limit, which is a Borel colored tree-semilattice (Theorem 2), and conversely: every Borel colored tree-semilattice is the limit of some QF-convergent sequence of colored weighted tree-semilattices (Corollary 2);
- every QF-convergent sequence of colored uniform tree-semilattices admits a limit, which is an atomless Borel colored tree-semilattice (Corollary 3), and conversely: every atomless Borel colored tree-semilattice is the limit of some finite QF-convergent sequence of colored uniform tree-semilattices (Theorem 1).

The notion of m -partite cographs has been introduced in [11], based on the generalization of the characterization of cographs by means of cotrees [8]: a graph G is an *m -partite cograph* if there exists a colored tree-semilattice \mathbf{T} , such that the vertices of G are the leaves of \mathbf{T} , the leaves of \mathbf{T} are colored

with a set of at most m colors, and the adjacency of any two vertices x and y is fully determined by the colors of x, y and $x \wedge y$. (Notice that there is no restriction on the colors used for internal elements of \mathbf{T} .) In this setting we prove (Theorem 5):

- every left-convergent sequence of m -partite cographs has a Borel limit, which is the interpretation of an atomless Borel colored tree-semilattice;
- conversely, every interpretation of an atomless Borel colored tree-semilattice is the left-limit of a sequence of m -partite cographs.

The class of all finite m -partite cographs can be characterized by means of a finite family \mathcal{F}_m of excluded induced subgraphs [12, 11]. We prove that this characterization extends to Borel graphs (Theorem 6) in the sense that an atomless Borel graph excludes all graphs in \mathcal{F}_m as induced subgraphs if and only if it is the interpretation of an atomless colored Borel tree-semilattice.

3. PRELIMINARIES

In a finite tree-semilattice, each element x except the minimum has a unique predecessor, that we call the *father* of x (as it is the father of x in the associated tree).

For a tree-semilattice \mathbf{T} and an element $v \in T$ we further define

$$\begin{aligned} T_v &= \{u \in T; u \geq v\} \\ F_v &= \{u \text{ minimal in } T_v \setminus \{v\}\}. \end{aligned}$$

Let \mathbf{T} be a tree-semilattice, and let $u_1, \dots, u_p \in T$. The *sub-tree-semilattice* $\mathbf{T}\langle u_1, \dots, u_p \rangle$ of \mathbf{T} generated by u_1, \dots, u_p is the tree-semilattice with elements

$$\left\{ \bigwedge_{i \in I} u_i; \quad \emptyset \neq I \subseteq \{1, \dots, p\} \right\},$$

where \wedge is defined as the restriction of the \wedge function of \mathbf{T} to the domain of $\mathbf{T}\langle u_1, \dots, u_p \rangle$.

Remark 1. *Condition (2) of the definition of a tree-semilattice can be replaced by condition:*

$$\forall x, y, z \in T \quad |\{x \wedge y, x \wedge z, y \wedge z\}| \leq 2.$$

It follows that for $u_1, \dots, u_p \in T$, the sub-tree-semilattice $\mathbf{T}\langle u_1, \dots, u_p \rangle$ of \mathbf{T} generated by u_1, \dots, u_p has domain

$$T \cup \{u_i \wedge u_j : 1 \leq i < j \leq p\}.$$

If $\phi \in \text{QF}_p$ is any quantifier-free formula with p free variables (in the language of tree-semilattice) and \mathbf{T} is a Borel tree-semilattice then $\phi(\mathbf{T})$ is a Borel subset of T^p , thus any (Borel) probability measure μ on \mathbf{T} allows to define

$$\langle \phi, (\mathbf{T}, \mu) \rangle = \mu^{\otimes p}(\phi(\mathbf{T})).$$

Let $\mathbf{T}_1, \mathbf{T}_2$ be Borel tree-semilattices, and let μ_1 and μ_2 be probability measures on T_1 and T_2 , respectively. We define the pseudometric

$$\text{dist}((\mathbf{T}_1, \mu_1), (\mathbf{T}_2, \mu_2)) = \sum_{p \geq 1} 2^{-p} \sup_{\phi \in \text{QF}_p} |\langle \varphi_p, (\mathbf{T}_1, \mu_1) \rangle - \langle \varphi_p, (\mathbf{T}_2, \mu_2) \rangle|.$$

Note that a sequence of Borel tree-semilattices is QF-convergent if and only if it is Cauchy for the above distance.

As mentioned in Section 2, the color of an element v of a colored tree-semilattice is the set $c(v)$ of the indices of those unary relations v belongs to. The order of the relations naturally induces a total order on these colors: for distinct $c_1, c_2 \subseteq \{1, \dots, k\}$ it holds $c_1 < c_2$ if $\min(c_1 \setminus c_2) < \min(c_2 \setminus c_1)$ (with convention $\min \emptyset = 0$).

4. SAMPLING AND APPROXIMATING

Two Borel structures \mathbf{A}, \mathbf{B} are *QF-equivalent* if $\langle \phi, \mathbf{A} \rangle = \langle \phi, \mathbf{B} \rangle$ holds for every quantifier free formula ϕ . The following lemma, which is trivial for uniform structures, requires some little work for structures with a probability measure. As it this result is not really needed here, we leave the proof to the reader.

Lemma 1. *Two finite structures are QF-equivalent if and only if they are isomorphic.*

Definition 1. *Let \mathbf{A} be a Borel structure, and let $n, L \in \mathbb{N}$. The (n, L) -sampling of \mathbf{A} is the random structure $\mathbf{B}_{X_1, \dots, X_n}$ defined as follows:*

- *the domain of $\mathbf{B}_{X_1, \dots, X_n}$ is the union of sets Ω, Γ , and $\{\perp\}$, where $\Omega = \{X_1, \dots, X_n\}$ is a set of n random independent elements of \mathbf{A} sampled with probability $\mu_{\mathbf{A}}$, Γ is the set of all the elements that can be obtained from Ω by at most L applications of a function, and \perp is an additional element;*
- *the relations are defined on $\mathbf{B}_{X_1, \dots, X_n}$ as in \mathbf{A} , as well as functions when the image belongs to $\Omega \cup \Gamma$. When undefined, functions have image \perp ;*
- *the probability measure on $\mathbf{B}_{X_1, \dots, X_n}$ assigns probability $1/n$ to X_1, \dots, X_n , and probability 0 to the other elements.*

Lemma 2 ([25]). *Let X_1, \dots, X_n be independent random variables, with X_k taking values in a set A_k for each k . Suppose that a (measurable) function $f : \prod A_k \rightarrow \mathbb{R}$ satisfies*

$$|f(\mathbf{x}) - f(\mathbf{x}')| \leq c_k$$

whenever the vectors \mathbf{x} and \mathbf{x}' differ only in the k th coordinate. Let Y be the random variable $f[X_1, \dots, X_n]$. Then for any $t > 0$,

$$\Pr(|Y - \mathbb{E}Y| \geq t) \leq 2e^{-2t^2 / \sum c_k^2}.$$

Lemma 3. *Let ϕ be a quantifier-free formula ϕ with at most p free variables and at most L functional symbols.*

Then, for every Borel structure \mathbf{A} and every $\epsilon > 0$ and $n > 2/\epsilon$, it holds

$$\Pr(|\langle \phi, \mathbf{A} \rangle - \langle \phi, \mathbf{B}_{X_1, \dots, X_n} \rangle| \geq \epsilon) \leq 2e^{-\frac{(\epsilon n - 2)^2}{p^2 n}},$$

where $\mathbf{B}_{X_1, \dots, X_n}$ is the (n, L) -sampling of \mathbf{A} .

Proof. Let $n \geq p$ and let f be the indicator function of $\phi(\mathbf{A})$. Then

$$\begin{aligned} \langle \phi, \mathbf{A} \rangle &= \int \cdots \int f(x_1, \dots, x_p) \, dx_1 \dots dx_p \\ &= \frac{1}{(n)_p} \int \cdots \int \sum_{g \in \text{Inj}([p], [n])} f(x_{g(1)}, \dots, x_{g(p)}) \, dx_1 \dots dx_n, \end{aligned}$$

where $(n)_p = n(n-1) \dots (n-p+1)$ is the Pochhammer symbol.

Let

$$h(x_1, \dots, x_n) = \frac{1}{n^p} \sum_{g \in [n]^{[p]}} f(x_{g(1)}, \dots, x_{g(p)}).$$

Then it holds

$$\langle \phi, \mathbf{B}_{X_1, \dots, X_n} \rangle = h(X_1, \dots, X_n).$$

Considering the expectation we get

$$\mathbb{E}h(X_1, \dots, X_n) = \frac{1}{n^p} \int \cdots \int \sum_{g \in [n]^{[p]}} f(x_{g(1)}, \dots, x_{g(p)}) \, dx_1 \dots dx_n.$$

So we have

$$\begin{aligned} |\langle \phi, \mathbf{A} \rangle - \mathbb{E}h(X_1, \dots, X_n)| &\leq \left(1 - \frac{(n)_p}{n^p}\right) \langle \phi, \mathbf{A} \rangle + \left| \frac{(n)_p}{n^p} \langle \phi, \mathbf{A} \rangle - \mathbb{E}h(X_1, \dots, X_n) \right| \\ &\leq \left(1 - \frac{(n)_p}{n^p}\right) \langle \phi, \mathbf{A} \rangle + \frac{|[n]^{[p]} - \text{Inj}([p], [n])|}{n^p} \\ &< \frac{2}{n} \end{aligned}$$

Now remark that for every $x_1, \dots, x_n, \hat{x}_i$ it holds

$$|h(x_1, \dots, x_i, \dots, x_n) - h(x_1, \dots, \hat{x}_i, \dots, x_n)| \leq \frac{p}{n},$$

as p/n bounds the probability that an mapping from $[p]$ to $[n]$ will map some value to i . Thus, according to Lemma 2 it holds for any $t > 0$:

$$\Pr(|h(X_1, \dots, X_n) - \mathbb{E}h(X_1, \dots, X_n)| \geq t) \leq 2e^{-\frac{2nt^2}{p^2}}.$$

In particular, for $t = \epsilon - 2/n$ it holds

$$\begin{aligned} \Pr(|\langle \phi, \mathbf{A} \rangle - \langle \phi, \mathbf{B}_{X_1, \dots, X_n} \rangle| \geq \epsilon) &\leq \Pr(|\mathbb{E}h(X_1, \dots, X_n) - h(X_1, \dots, X_n)| \geq \epsilon - 2/n) \\ &\leq 2e^{-\frac{(\epsilon n - 2)^2}{p^2 n}}. \end{aligned}$$

□

By union bound, we deduce that for sufficiently large n there exists an (n, L) -sampling which has ϵ -close Stone pairing with any formula with at most p free variables and at most L functional symbols. Precisely, we have:

Corollary 1. *For every signature σ there exists a function $R : \mathbb{N} \times \mathbb{N} \rightarrow \mathbb{N}$ with the following property:*

For every Borel σ -structure \mathbf{A} , every $\epsilon > 0$ and every $L \in \mathbb{N}$ there exists, for each $n \geq R(p, L) \epsilon^{-2}$ an (n, L) -sampling \mathbf{B} of \mathbf{A} such that for every formula ϕ with at most p free variables and L functional symbols it holds

$$|\langle \phi, \mathbf{A} \rangle - \langle \phi, \mathbf{B} \rangle| < \epsilon.$$

Hence we have:

Corollary 2. *Every Borel σ -structure is the limit of a sequence of weighted finite σ -structures.*

Note that the finite weighted structures obtained as (n, L) -sampling of a Borel structure \mathbf{A} usually have many elements with 0 measure. The problem of determining whether an infinite Borel structure \mathbf{A} is the limit of a sequence of finite unweighted structures is much more difficult. Note that we have some (easy) necessary conditions on \mathbf{A} :

- the domain A is uncountable and the measure $\mu_{\mathbf{A}}$ is atomless;
- for every definable functions $f, g : A^r \rightarrow A^r$, and every definable subset $X \subseteq A^r$ of the set of fixed points of $f \circ g$, the sets X and $g(X)$ have the same measure.

The second condition can be seen as a simple generalization of the *intrinsic mass transport principle* of Benjamini and Schramm: a graphing indeed defines a purely functional structure, with d functional symbols, each interpreted as a measure preserving involution. In this case, the existence for each graphing of a sequence of bounded degree graphs having the given graphing as its limits is the difficult and well-known Aldous-Lyons conjecture [2]. It turns out that one of the main difficulties of this problem concerns the expansion properties of the graphing. This leads naturally to first consider a weakened version we present now (for generalized structures):

Let \mathbf{A} be a σ -structure and let $v_1, \dots, v_p \in A$. The *substructure* of \mathbf{A} generated by v_1, \dots, v_p is the σ -structure, denoted $\mathbf{A}[v_1, \dots, v_p]$, whose domain is the smallest subset of A including $\{v_1, \dots, v_p\}$ closed by all functional symbols of σ , with the same interpretation of the relations and functions symbols as \mathbf{A} .

We shall now prove that in the case of atomless Borel tree semi-lattices, the sampling techniques can be used to build arbitrarily good finite approximations, thus to build a converging sequence of finite tree semi-lattices with the given Borel semi-lattice as a limit.

Theorem 1. *Every atomless Borel tree-semilattice (\mathbf{T}, μ) is limit of a sequence of uniform finite Borel tree-semilattices.*

Proof. Let (\mathbf{T}_N, μ_N) be an $(N, 1)$ -sampling of (\mathbf{T}, μ) (note that in the context of tree-semilattices, and according to Remark 1, taking $L > 1$ yields the same structures as with $L = 1$). Let $M = |S| - N$, that is, the number of vertices of \mathbf{T}_N that were not directly sampled.

Fix $C \in \mathbb{N}$ and let $[C] = \{1, \dots, C\}$. Let $(\hat{\mathbf{T}}_N, \hat{\mu}_N)$ be the Borel tree-semilattice with elements set $\hat{T}_N \subseteq T_n \times [C]$ defined by:

$$\hat{T}_N = \{x \in T_N : \mu_N(\{x\}) = 0\} \times \{1\} \cup \{x \in T_N : \mu_N(\{x\}) > 0\} \times [C]$$

with meet operation defined by

$$(x, i) \wedge (y, j) = \begin{cases} (x \wedge y, 1) & \text{if } x \wedge y \notin \{x, y\} \\ (x, i) & \text{if } x \wedge y = x \text{ and } x \neq y \\ (y, j) & \text{if } x \wedge y = y \text{ and } x \neq y \\ (x, \max(i, j)) & \text{if } x = y \end{cases}$$

and uniform measure $\hat{\mu}_N$.

Informally, $(\hat{\mathbf{T}}_N, \hat{\mu}_N)$ is obtained from (\mathbf{T}_N, μ_N) by replacing each of the randomly selected elements used to create \mathbf{T}_N with a chain on c vertices, and considering a uniform measure.

Define the map

$$\pi : \hat{T}_N \rightarrow T_N, \quad (x, i) \mapsto x.$$

Note that for every quantifier free formula ϕ with p free variables, it holds, for every distinct $u_1, \dots, u_p \in T_N$ and every $v_1 \in \pi^{-1}(u_1), \dots, v_p \in \pi^{-1}(u_p)$ it holds:

$$\mathbf{T}_N \models \phi(u_1, \dots, u_p) \iff \hat{\mathbf{T}}_N \models \phi(v_1, \dots, v_p).$$

Let \mathbf{L} be a Borel tree-semilattice, p an integer, and X_1, \dots, X_p (resp. Y_1, \dots, Y_p) independent random variables in T_N (resp. \hat{T}_N) (with $X_i(\omega) = \mu_N(\omega)$, resp. $Y_i(\omega) = \hat{\mu}_N(\omega)$). Let ϕ be a quantifier-free formula. As for any formula ψ and any structure \mathbf{A} it holds $\langle \phi, \mathbf{A} \rangle - \langle \phi \& \psi, \mathbf{A} \rangle \leq \langle \neg\psi, \mathbf{A} \rangle$, we have

$$\begin{aligned} & \left| \Pr(\mathbf{T}_N \models \phi(X_1, \dots, X_p)) - \Pr(\mathbf{T}_N \models \phi(X_1, \dots, X_p) \& \neg \bigvee_{i \neq j} (X_i = X_j)) \right| \\ & \leq \Pr\left(\bigvee_{1 \leq i < j \leq p} (X_i = X_j)\right) \leq \binom{p}{2} \Pr(X_1 = X_2) \leq \frac{p^2}{2N} \end{aligned}$$

Similarly, denoting B the event

$$\bigvee_{1 \leq i < p} (\pi(Y_i) = \pi(Y_j)) \vee \bigvee_{i=1}^p (\mu_N(\pi(Y_i)) = 0)$$

it holds

$$\begin{aligned} & \left| \Pr\left(\hat{\mathbf{T}}_N \models \phi(Y_1, \dots, Y_p)\right) - \Pr\left(\mathbf{T}_N \models \phi(Y_1, \dots, Y_p) \ \& \ \neg B\right) \right| \\ & \leq \Pr(B) \leq \frac{pM}{CN + M} + \frac{p^2}{2N} \leq \frac{p}{N} \left(\frac{M}{C} + \frac{p}{2} \right) \end{aligned}$$

But, denoting by I_A the indicator function of set A , it holds:

$$\begin{aligned} & \Pr\left(\mathbf{T}_N \models \phi(X_1, \dots, X_p) \ \& \ \neg \bigvee_{i \neq j} X_i = X_j\right) \\ &= \sum_{f \in \text{Inj}([p], T_N)} \left(\prod_{i=1}^p \mu_N(\{f(i)\}) \right) I_{\phi(\mathbf{T}_n)}(f(1), \dots, f(p)) \\ &= \frac{1}{N^p} \sum_{f \in \text{Inj}([p], T_N)} I_{\phi(\mathbf{T}_n)}(f(1), \dots, f(p)) \\ &= \frac{1}{(CN)^p} \sum_{f \in \text{Inj}([p], T_N)} \sum_{g \in [C]^{[p]}} I_{\phi(\mathbf{T}_n)}(f(1), \dots, f(p)) \\ &= \frac{1}{(CN)^p} \sum_{f \in \text{Inj}([p], T_N)} \sum_{g \in [C]^{[p]}} I_{\phi(\hat{\mathbf{T}}_n)}((f(1), g(1)), \dots, (f(p), g(p))) \\ &= \frac{(CN + M)^p}{(CN)^p} \Pr\left(\hat{\mathbf{T}}_N \models \phi(Y_1, \dots, Y_p) \ \& \ \neg B\right). \end{aligned}$$

Thus

$$\begin{aligned} & \left| \Pr\left(\mathbf{T}_N \models \phi(X_1, \dots, X_p) \ \& \ \neg \bigvee_{i \neq j} X_i = X_j\right) - \Pr\left(\hat{\mathbf{T}}_N \models \phi(Y_1, \dots, Y_p) \ \& \ \neg B\right) \right| \\ & \leq \left(\frac{CN + M}{CN} \right)^p - 1 \leq \frac{pM}{CN} \end{aligned}$$

Altogether, we have:

$$\left| \Pr\left(\mathbf{T}_N \models \phi(X_1, \dots, X_p)\right) - \Pr\left(\hat{\mathbf{T}}_N \models \phi(Y_1, \dots, Y_p)\right) \right| \leq \frac{p}{N} \left(p + \frac{2M}{C} \right).$$

In other words, it holds

$$\left| \langle \phi, (\mathbf{T}_N, \mu_N) \rangle - \langle \phi, \hat{\mathbf{T}}_N \rangle \right| \leq \frac{p}{N} \left(p + \frac{2M}{C} \right).$$

Together with Corollary 2, we get that for every atomless Borel tree semi-lattice (\mathbf{T}, μ) , every $\epsilon > 0$ and every $p \in \mathbb{N}$ there exists a finite (unweighted) tree semi-lattice $\hat{\mathbf{T}}$ such that for every quantifier free formula ϕ with p free variables it holds

$$\left| \langle \phi, \mathbf{T} \rangle - \langle \phi, \hat{\mathbf{T}} \rangle \right| < \epsilon,$$

hence if we choose $p > -\log_2 \epsilon$ it holds $\text{dist}(\mathbf{T}, \hat{\mathbf{T}}) < \epsilon + 2^{-p} < 2\epsilon$. \square

5. LIMITS OF TREE-SEMILATTICES

In this section, we focus on providing an approximation lemma for finite colored tree-semilattices, which can be seen as an analog of the weak version of Szemerdi's regularity lemma. For the sake of simplicity, in this section, by tree-semilattice we always mean a finite weighted colored tree-semilattice.

5.1. Partitions of tree-semilattices.

Definition 2. Let (\mathbf{T}, μ) be a tree-semilattice and let $\epsilon > 0$. Then $v \in T$ is said:

- ϵ -light if $\mu(T_v) < \epsilon$;
- ϵ -singular if $\mu(T'_v) \geq \epsilon$ where T'_v is the set T_v minus the sets T_u for non- ϵ -light children u of v ;
- ϵ -chaining if v is not singular and has exactly 1 non-light child;
- ϵ -branching if v is not singular and has at least 2 non-light children.

(One can easily convince themselves that every vertex of a tree-semilattice falls in exactly one of those categories.)

Definition 3. Let (\mathbf{T}, μ) be a tree-semilattice. A partition \mathcal{P} of T is an ϵ -partition of (\mathbf{T}, μ) if

- each part is of one of the following types (for some $v \in T$, see Fig. 1):
 - (1) $P = \{v\}$,
 - (2) $P = \{v\} \cup \bigcup_{x \in F} T_x$ for some non-empty $F \subseteq F_v$,
 - (3) $P = \bigcup_{x \in F} T_x$ for some $F \subseteq F_v$ with $|F| \geq 2$,
 - (4) $P = T_v \setminus T_w$ for some $w \in T_v$ distinct from v (w is called the cut vertex of P , and the path from v to the father of w is called the spine of P),
 where v (which is easily checked to be the infimum of P) is called the attachment vertex of P and is denoted by $A_{\mathcal{P}}(P)$;
- each attachment vertex of a part of type 3 is also the attachment vertex of some part of type 1 or 2;
- every part which is not a singleton has μ -measure at most ϵ .

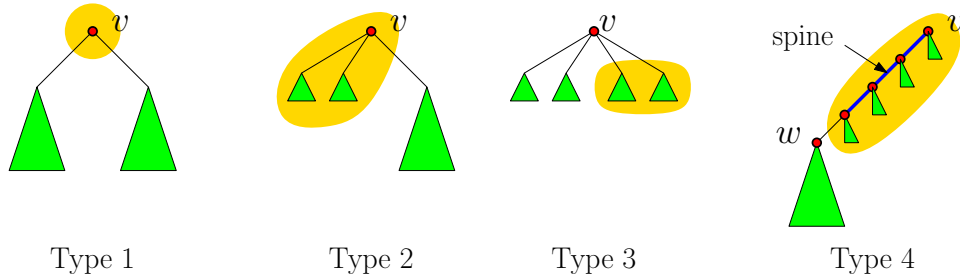


FIGURE 1. Types of part in an ϵ -partition

An ϵ -partition \mathcal{P} of a tree-semilattice (\mathbf{T}, μ) canonically defines a quotient rooted tree:

Definition 4. Let \mathcal{P} be an ϵ -partition of a tree-semilattice (\mathbf{T}, μ) . The quotient rooted tree \mathbf{T}/\mathcal{P} is the rooted tree with node set \mathcal{P} , the root of which is the unique part of \mathcal{P} that contains the minimum element of \mathbf{T} , where the father of any non-root part P is the part that contains the father of $A_{\mathcal{P}}(P)$ if $A_{\mathcal{P}}(P) \notin P$ (i.e. types 1, 2, or 4) or $A_{\mathcal{P}}(P)$ itself if $A_{\mathcal{P}}(P) \in P$ (i.e. type 3). By abuse of notation, \mathbf{T}/\mathcal{P} will also denote the tree-semilattice defined by the ancestor relation in the rooted tree \mathbf{T}/\mathcal{P} .

In several circumstances it will be handy to refer to an ϵ -partition \mathcal{P} of a tree-semilattice (\mathbf{T}, μ) directly by means of the partition map $f : T \rightarrow \mathcal{P}$ (where \mathcal{P} is meant as the vertex set of \mathbf{T}/\mathcal{P}). Note that this mapping is a *weak homomorphism* in the sense that for every $x, y \in T$ it holds $f(x \wedge y) = f(x) \wedge f(y)$ except (maybe) in the case where $f(x) = f(y)$. The definition of ϵ -partitions can easily be transposed to provide a characterization of those weak homomorphisms $f : \mathbf{T} \rightarrow \tilde{\mathbf{T}}$ that define an ϵ -partition. Such mappings are called *ϵ -partition functions*.

We now prove that every tree-semilattice has a small ϵ -partition.

Lemma 4. Let (\mathbf{T}, μ) be a tree-semilattice and $\epsilon > 0$. Then there exists an ϵ -partition $\mathcal{P}_{\epsilon}(\mathbf{T}, \mu)$ of (\mathbf{T}, μ) with at most $4/\epsilon$ elements.

Proof. For sake of clarity, we construct the desired ϵ -partition in two steps. First, let \mathcal{P} be the partition of T obtained in the following manner:

- for every ϵ -singular vertex v , keep $\{v\}$ in its own part, and, for an arbitrary order on the ϵ -light children of u , group the $\{T_u; u \text{ } \epsilon\text{-light child of } v\}$ greedily such that the μ -measure of each part is maximum while remaining less than ϵ .
- for every ϵ -branching or ϵ -chaining vertex v , group v with $\{T_u; u \text{ } \epsilon\text{-light child of } v\}$,

It is easily seen that \mathcal{P} is indeed an ϵ -partition of (\mathbf{T}, μ) (with only parts of type 1, 2, 3). However, the number of parts is not bounded by $O(1/\epsilon)$.

Now, as per the definition, an ϵ -chaining vertex has at most one ϵ -chaining child, and the previous construction never groups the two together. Hence, we can consider chains of parts rooted at ϵ -chaining vertices, the parts of which we merge greedily (starting from the closest to the root, and going from parent to child) so that each part has maximum μ -measure while remaining less than ϵ , thus yielding a partition $\mathcal{P}_{\epsilon}(\mathbf{T}, \mu)$, in which every part is either:

- (1) an ϵ -singular vertex alone,
- (2) a subtree of T rooted at an ϵ -branching vertex,
- (3) or $\bigcup_{x \in F} T_x$ for F a set of children of some ϵ -singular vertex.
- (4) $T_u \setminus T_v$ for an ϵ -chaining vertex u and a descendent v of u ,

Note that these four categories correspond exactly to the 4 types described in Definition 3, and since by definition, all parts are indeed of μ -measure

at most ϵ , we get an ϵ -partition of (\mathbf{T}, μ) . Now we need to prove that the number of parts is bounded.

First, note that there are at most $1/\epsilon$ sets of the first kind. Indeed, to each singular vertex v correspond a subtree (T_v minus the sets T_u for non- ϵ -light children u of v) of measure at least ϵ , and each of these subtrees are disjoint.

Sets of type 2 correspond to ϵ -branching vertices. Consider the tree obtained by deleting ϵ -light vertices. We obtain a rooted tree, in which every chaining vertex has exactly one child, branching vertices have at least two children, and leaves are necessarily singular vertices. Therefore the number of branching vertices is at most the number of singular vertices, hence there are at most $1/\epsilon$ sets of type 2.

Finally, note that in the greedy construction of sets of both types 3 or 4, we apply a similar principle : we have a collection of disjoint sets, each of measure at most ϵ , and of total measure, say p , and we partition this collection by forming groups of total measure at most ϵ . It is an easy observation that this can be done using at most $2p/\epsilon$ groups : one can sets greedily by decreasing order of measure – this insures that all groups but the last have weight at least $\epsilon/2$. Moreover these groups are overall all disjoint (a non-light vertex cannot be the descendent of a light one), so the total number of parts of type 3 and 4 is at most $2/\epsilon$. This concludes our proof. \square

A partition \mathcal{P} is said to be a *refinement* of another one \mathcal{P}' if each element of \mathcal{P} is a subset of an element of \mathcal{P}' .

Lemma 5. *Let $\epsilon' < \epsilon$, \mathbf{T} be a (finite) tree-semilattice, and \mathcal{P} be an ϵ -partition of \mathbf{T} . Then there exists an ϵ' -partition \mathcal{P}' of \mathbf{T} with at most $81/\epsilon'$ elements, that is a refinement of \mathcal{P} . Moreover, \mathcal{P} induces an ϵ -partition of the tree-semilattice T/\mathcal{P}' .*

Proof. Each part not of type 3 is a tree with total measure at most ϵ , so we can apply Lemma 4 independently on each of these trees. For parts of type 3, we start by putting the attachment vertex back in the part, and then again apply Lemma 4, before removing it. Thus, we obtain an ϵ' -partition of \mathbf{T} with at most $16/\epsilon'$ elements. \square

5.2. Approximations. In the previous subsection, we defined ϵ -partitions and described the quotient map and quotient tree associated to an ϵ -partition. These are convenient objects to represent the partition (in particular with respects to successive refinement) but they miss some information about the measure and the colors. This is why we introduce here the concept of f -reduction. We first give the definition and give two easy but essential lemmas before showing how to construct the particular "small" reductions that will be of use to construct approximations in the proof of our main Theorem.

Definition 5. *Let (\mathbf{T}, μ) be a tree-semilattice and let $f : \mathbf{T} \rightarrow \tilde{\mathbf{T}}$ be an ϵ -partition function of (\mathbf{T}, μ) .*

An f -reduction of \mathbf{T} is a color-preserving mapping $\pi : \mathbf{T} \rightarrow \hat{\mathbf{T}}$, where $\hat{\mathbf{T}}$ is a tree-semilattice, such that f factorizes as $\hat{f} \circ \pi$, where \hat{f} is an ϵ -partition function of $(\hat{\mathbf{T}}, \mu \circ \pi^{-1})$, and π satisfies the property that for every $x, y \in T$ with $f(x) \neq f(y)$ it holds

$$\begin{aligned} \pi(x \wedge y) &= \pi(x) \wedge \pi(y) \\ x \leq y &\iff \pi(x) \leq \pi(y) \end{aligned}$$

Such a situation we depict by the following commutative diagram:

$$\begin{array}{ccc} \mathbf{T} & \xrightarrow{\pi} & \hat{\mathbf{T}} \\ f \downarrow & \searrow \hat{f} & \\ \tilde{\mathbf{T}} & & \end{array}$$

Lemma 6. Let (\mathbf{T}, μ) be a tree-semilattice, let $\epsilon > 0$, let $f : \mathbf{T} \rightarrow \tilde{\mathbf{T}}$ be an ϵ -partition function of (\mathbf{T}, μ) , let $\pi : \mathbf{T} \rightarrow \hat{\mathbf{T}}$ be an f -reduction of \mathbf{T} , and let $v_1, \dots, v_p \in T$ be such that $f(v_i) \neq f(v_j)$ whenever $v_i \neq v_j$.

Then π induces an isomorphism of $\mathbf{T}\langle v_1, \dots, v_p \rangle$ and $\hat{\mathbf{T}}\langle \pi(v_1), \dots, \pi(v_p) \rangle$

Proof. By assumption, for every distinct v_i, v_j it holds $f(v_i) \neq f(v_j)$ thus $\pi(v_i \wedge v_j) = \pi(v_i) \wedge \pi(v_j)$. As π is color preserving, in order to prove that π is an homomorphism, we only have to check (as \wedge is associative) that if $x \in \mathbf{T}\langle v_1, \dots, v_p \rangle$ and $1 \leq k \leq p$ then $\pi(x \wedge v_k) = \pi(x) \wedge \pi(v_k)$. According to Remark 1, there exist i, j such that $x = v_i \wedge v_j$. Moreover, there exists a permutation i', j', k' of i, j, k such that $v_i \wedge v_j \wedge v_k = v_{i'} \wedge v_{k'} = v_{j'} \wedge v_{k'}$. Hence $\pi(v_i \wedge v_j \wedge v_k) = \pi(v_{i'} \wedge v_{k'}) = \pi(v_{i'}) \wedge \pi(v_{k'})$ and similarly $\pi(v_i \wedge v_j \wedge v_k) = \pi(v_{j'}) \wedge \pi(v_{k'})$. Thus $\pi(x \wedge v_k) = \pi(v_i \wedge v_j \wedge v_k) = \pi(v_{i'}) \wedge \pi(v_{j'}) \wedge \pi(v_{k'}) = \pi(v_i \wedge \pi(v_j) \wedge \pi(v_k)) = \pi(x) \wedge \pi(v_k)$.

In order to prove that π is an isomorphism, we have to check that π is injective, that is, according to Remark 1, that $\pi(v_i \wedge v_j) = \pi(v_k \wedge v_\ell)$ not only implies $f(v_i \wedge v_j) = f(v_k \wedge v_\ell)$, but also implies $v_i \wedge v_j = v_k \wedge v_\ell$. Let v_i, v_j, v_k, v_ℓ be all distinct. Then $f(v_i \wedge v_j)$ is of type 1 or 2, thus $v_i \wedge v_j$ and $v_k \wedge v_\ell$ coincides with the attachment vertex of $f(v_i \wedge v_j)$ thus $v_i \wedge v_j = v_k \wedge v_\ell$. Also, if $\pi(v_i \wedge v_j) = \pi(v_k)$ then $f(v_k)$ has type 1 or 2. As $\pi(v_k) \leq \pi(v_i)$ it holds $v_k \leq v_i$ hence v_k is the attachment vertex of $f(v_k)$ thus $v_k = v_i \wedge v_j$. If $\pi(v_i \wedge v_k) = \pi(v_j \wedge v_k)$ then either $f(v_i \wedge v_k)$ has type 1 or 2, in which case $v_i \wedge v_k = v_j \wedge v_k$, or $f(v_i \wedge v_k)$ has type 4 and again $v_i \wedge v_k = v_j \wedge v_k$. Last, if $\pi(v_i \wedge v_j) = \pi(v_j)$ then $\pi(v_j) \leq \pi(v_i)$ thus $v_j \leq v_i$, that is $v_i \wedge v_j = v_j$. \square

Lemma 7. Let (\mathbf{T}, μ) be a tree-semilattice, let $\epsilon > 0$, let $f : \mathbf{T} \rightarrow \tilde{\mathbf{T}}$ be an ϵ -partition function of (\mathbf{T}, μ) , let $\pi : \mathbf{T} \rightarrow \hat{\mathbf{T}}$ be an f -reduction of \mathbf{T} , and let $\hat{\mu} = \mu \circ \pi^{-1}$.

Then for every quantifier free formula $\phi \in \text{QF}_p$ it holds

$$|\langle \phi, (\mathbf{T}, \mu) \rangle - \langle \phi, (\hat{\mathbf{T}}, \hat{\mu}) \rangle| < p^2 \epsilon.$$

Thus,

$$\text{dist}((\mathbf{T}, \mu), (\hat{\mathbf{T}}, \hat{\mu})) < 6\epsilon.$$

Proof. Let $\hat{f} : \hat{\mathbf{T}} \rightarrow \tilde{\mathbf{T}}$ be the ϵ -partition function associated to the f -reduction. Define the sets

$$A = \{(v_1, \dots, v_p) \in \phi(\mathbf{T}) : \forall i \neq j (f(v_i) = f(v_j)) \rightarrow (v_i = v_j)\}$$

$$\hat{A} = \{(z_1, \dots, z_p) \in \phi(\hat{\mathbf{T}}) : \forall i \neq j (\hat{f}(z_i) = \hat{f}(z_j)) \rightarrow (z_i = z_j)\}$$

According to Lemma 6, it holds $\mu^{\otimes p}(A) = \hat{\mu}^{\otimes p}(\hat{A})$. As

$$\begin{aligned} & |\langle \phi, (\mathbf{T}, \mu) \rangle - \mu^{\otimes p}(A)| \\ & \leq \mu^{\otimes p}(\{(v_1, \dots, v_p) \in T : \exists i \neq j (f(v_i) = f(v_j)) \wedge \neg(v_i = v_j)\}) \\ & \leq \binom{p}{2} \max\{\mu(f^{-1}(p)) : p \in \tilde{\mathbf{T}} \text{ and } |f^{-1}(p)| > 1\} \\ & < p^2\epsilon/2 \end{aligned}$$

and as the same holds for $|\langle \phi, (\hat{\mathbf{T}}, \hat{\mu}) \rangle - \hat{\mu}^{\otimes p}(\hat{A})|$ we deduce that $|\langle \phi, (\mathbf{T}, \mu) \rangle - \langle \phi, (\hat{\mathbf{T}}, \hat{\mu}) \rangle| < p^2\epsilon$. As $\sum_p p^2 2^{-p} = 6$ the bound on the distance follows. \square

We can now define the particular f -reductions, called *standard f -reductions* that we will consider to construct approximations. The fact that this construction yields indeed an f -reduction is proven in Lemma 8.

Definition 6. Let (\mathbf{T}, μ) be a tree-semilattice, let $\epsilon > 0$, and let $f : \mathbf{T} \rightarrow \tilde{\mathbf{T}}$ be an ϵ -partition function of (\mathbf{T}, μ) .

The standard f -reduction $\pi : \mathbf{T} \rightarrow \hat{\mathbf{T}}$ of (\mathbf{T}, μ) is defined as follows. For each part P of \mathcal{P} we associate a rooted tree (or a rooted forest) \mathbf{Y}_P and we define the projection π from T to the domain $\hat{T} = \bigcup Y_P$ of $\hat{\mathbf{T}}$ as follows:

- If P is of type 1 ($P = \{v\}$):
Then \mathbf{Y}_P is a single-node rooted tree, π maps v to the only vertex in \mathbf{Y}_P , which is assigned the same color and weight as v .
- If P is of type 2 ($P = \{v\} \cup \bigcup_{x \in F} T_x$):
Then \mathbf{Y}_P is rooted at a vertex a_P (having same color and weight as v) that has, for each color γ present in $P \setminus \{v\}$, a child $b_{P,\gamma}$ of color γ whose weight is the sum of the weights of γ -colored vertices of $P \setminus \{v\}$; the projection π maps v to a_P and $u \in P \setminus \{v\}$ to $b_{P,c(u)}$.
- If P is of type 3 ($P = \bigcup_{x \in F} T_x$):
Then \mathbf{Y}_P is a set of single node rooted trees, with roots $b_{P,\gamma_1}, \dots, b_{P,\gamma_\ell}$, where $\gamma_1, \dots, \gamma_\ell$ are the colors present in P . The projection π maps each vertex $u \in P$ to $b_{P,c(u)}$, and the weight of b_{P,γ_i} is defined as the sum of the weights of the $u \in P$ with color γ_i .
- If P is of type 4 ($P = T_v \setminus T_w$):
Then \mathbf{Y}_P is a rooted caterpillar with spine $a_{P,\gamma_1}, \dots, a_{P,\gamma_\ell}$ rooted at a_{P,γ_1} , where $\gamma_1, \dots, \gamma_\ell$ are the colors present in the spine S of P ; the projection π maps each vertex $u \in S$ to $a_{P,c(u)}$, and the weight of

a_{P,γ_i} is defined as the sum of the weights of the $u \in S$ with color γ_i . Each vertex a_{P,γ_i} has sons $b_{P,\gamma_i,\rho_{i,j}}$ ($1 \leq j \leq s_i$) where $\rho_{i,1}, \dots, \rho_{i,s_i}$ are the (distinct) colors of the vertices $u \in P \setminus S$ such that $u \wedge w$ has color γ_i . The projection π maps each $u \in P \setminus S$ to $b_{P,c(u \wedge w),c(u)}$.

The colored tree-semilattice $\hat{\mathbf{T}}$ is defined by the rooted tree $\mathbf{T}_{\mathcal{P}}$, which is constructed from the disjoint union $\bigcup_{P \in \mathcal{P}} \mathbf{Y}_P$ as follows: For each non root part P of \mathcal{P} with father part P' , the node of $\mathbf{Y}_{P'}$ that will serve as the father of the root(s) of \mathbf{Y}_P is defined as follows: if P' has type 1 or 2, then the father of the root of \mathbf{Y}_P is the root of $\mathbf{Y}_{P'}$; if P is of type 4, then the father of the root of \mathbf{Y}_P is the maximum vertex of the spine of $\mathbf{Y}_{P'}$.

Before proving properties of standard f -reductions, let us illustrate our definitions by an example drawn on Figure 2. The tree \mathbf{T} has 80 vertices with uniform weight $1/80$ and suppose $\epsilon = 1/5$. Consider for instance the

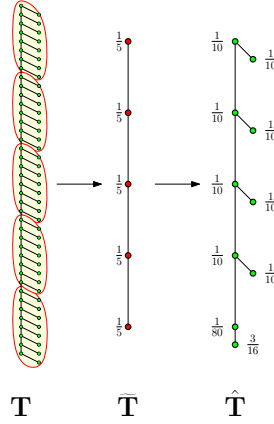


FIGURE 2. Example of $\mathbf{T}, \tilde{\mathbf{T}}, \hat{\mathbf{T}}$.

formula $\phi : (x_1 \wedge x_2 \neq x_1) \ \& \ (x_1 \wedge x_2 \neq x_2)$. Then $\langle \phi, \mathbf{T} \rangle = 0.4875$ and $\langle \phi, \hat{\mathbf{T}} \rangle = 0.4$ are close, but $\langle \phi, \tilde{\mathbf{T}} \rangle = 0$.

Lemma 8. *Let (\mathbf{T}, μ) be a tree-semilattice, let $\epsilon > 0$, and let $f : \mathbf{T} \rightarrow \tilde{\mathbf{T}}$ be an ϵ -partition function of (\mathbf{T}, μ) .*

Then the standard f -reduction $\pi : \mathbf{T} \rightarrow \hat{\mathbf{T}}$ of \mathbf{T} is an f -reduction and

$$|\hat{T}| \leq C(C+1)|\tilde{T}|,$$

where C denotes the number of colors for elements of T .

Proof. Let $\hat{\mu} = \mu \circ \pi^{-1}$. As $\pi(x) = \pi(y)$ imply $f(x) = f(y)$ there exists a mapping $\hat{f} : \hat{\mathbf{T}} \rightarrow \tilde{\mathbf{T}}$ such that $f = \hat{f} \circ \pi$. Moreover, it is easily checked that \hat{f} is an ϵ -partition function of $(\hat{\mathbf{T}}, \hat{\mu})$.

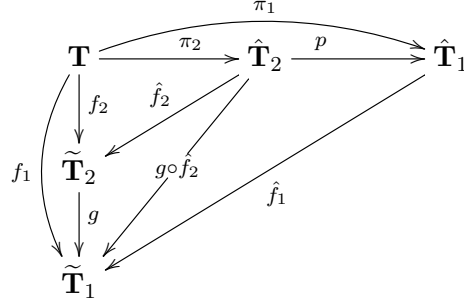
For every u, v in T with $f(u) \neq f(v)$, the element $\pi(u) \wedge \pi(v)$ belongs to the part $Y_{\pi(u \wedge v)}$, which has the same type as the part P of $u \wedge v$. If P has type 1 or

2 then $u \wedge v = A_P(P)$ and $\pi(u) \wedge \pi(v) = A_{\hat{P}}(Y_{\pi(u \wedge v)}) = \pi(A_P(P)) = \pi(u \wedge v)$. If P has type 3 then one of u and v has to belong to P (as P has only one child) and the other one has to belong to a part greater than P . Without loss of generality assume $u > v$ and $v \in P$. Then $u \wedge v = w \wedge v$, where w denotes the cut-vertex of P . Similarly, we have $\pi(u) \wedge \pi(v) = \hat{w} \wedge \pi(v)$, where \hat{w} denotes the cut-vertex of Y_P . By construction, it holds $\pi(w \wedge v) = \hat{w} \wedge \pi(v)$ hence $\pi(u \wedge v) = \pi(u) \wedge \pi(v)$. It follows that π is an f -reduction. \square

Lemma 9. *Let (\mathbf{T}, μ) be a tree-semilattice, let $\epsilon > 0$, let $f_1 : \mathbf{T} \rightarrow \hat{\mathbf{T}}_1$ (resp. $f_2 : \mathbf{T} \rightarrow \tilde{\mathbf{T}}_2$) be an ϵ_1 -partition function (resp. an ϵ_2 -partition function) of (\mathbf{T}, μ) .*

Let $\pi_1 : \mathbf{T} \rightarrow \hat{\mathbf{T}}_1$ (resp. $\pi_2 : \mathbf{T} \rightarrow \hat{\mathbf{T}}_2$) be the standard f_1 -reduction (resp. the standard f_2 -reduction) of \mathbf{T} .

If there exists a mapping $g : \tilde{\mathbf{T}}_2 \rightarrow \tilde{\mathbf{T}}_1$ (i.e. if partition f_2 refines partition f_1) then the standard $(g \circ \hat{f}_2)$ -reduction p of \mathbf{T} maps $\hat{\mathbf{T}}_2$ onto $\hat{\mathbf{T}}_1$ in such a way that the following diagram commutes:



Proof. The tedious but easy check is omitted here. \square

5.3. Limits of Tree-Semilattices.

Theorem 2. *Every QF-convergent sequence (\mathbf{T}_n, μ_n) of tree-semilattices has a Borel tree-semilattice limit $(\hat{\mathbf{T}}, \hat{\mu})$.*

Proof. We consider a decreasing sequence $\epsilon_1 > \epsilon_2 > \dots$ of positive reals with limit 0. Using Lemma 4 and Lemma 5, we can construct a sequence $\mathcal{P}_{n,1}, \mathcal{P}_{n,2}, \dots$ of partitions such that $\mathcal{P}_{n,i}$ is an ϵ_i -partition of (\mathbf{T}_n, μ_n) with at most $16/\epsilon_i$ vertices and $\mathcal{P}_{n,i+1}$ is a refinement of $\mathcal{P}_{n,i}$.

For every fixed i there are only a finite number of trees on $16/\epsilon_i$ vertices, so up to extracting subsequences (we do it sequentially starting with $i = 1$), we can assume that all the ϵ_i -partition functions corresponding to the $(\mathcal{P}_{n,i})_{n \in \mathbb{N}}$ have the same target tree $\tilde{\mathbf{T}}_i$.

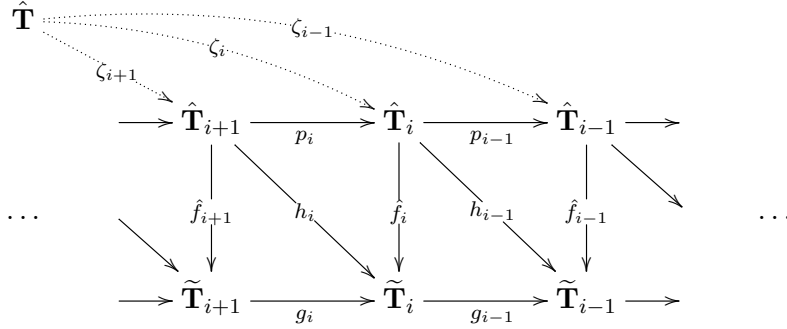
And in fact the same finiteness argument is true also for standard reductions, so we can also assume that all the standard $f_{n,i}$ -reductions $\pi_{n,i}$ have the same target $\hat{\mathbf{T}}_i$ (and partition map \hat{f}_i), and by a compactness argument we can also assume that for each i the measures $\hat{\mu}_{n,i}$ converge weakly to

some measure $\hat{\mu}_i$. We further denote by g_i the map from $\tilde{\mathbf{T}}_{i+1}$ to $\tilde{\mathbf{T}}_i$ witnessing that \mathcal{P}_{i+1} is a refinement of \mathcal{P}_i , by h_i the composition $g_i \circ \hat{f}_{i+1}$, and by $p_i : \hat{\mathbf{T}}_{i+1} \rightarrow \hat{\mathbf{T}}_i$ the standard h_i -reduction of $\hat{\mathbf{T}}_{i+1}$.

We define the set \hat{T} as

$$\hat{T} = \left\{ u \in \prod_{i \in \mathbb{N}} \hat{T}_i : (\forall n \in \mathbb{N}) p_n(u_{n+1}) = u_n \right\},$$

and we denote by $\zeta_i : \hat{T} \rightarrow \hat{T}_i$ the projection to the n th coordinate. Then we have the following diagram:



Note that \hat{T} (with product topology) is a Cantor space, hence (with Borel σ -algebra) is a standard Borel space. We define the color $c(u)$ of $u \in \hat{T}$ as the color of u_1 . As all mappings p_n are color-preserving, it follows that $c(u)$ is the color common to all of the u_n .

For $u, v \in \hat{T}$, and $n \in \mathbb{N}$, we note $u_n \sim v_n$ if :

- $\hat{f}_n(u_n) = \hat{f}_n(v_n)$
- either u_n and v_n are equal or $\hat{f}_n(v_n)$ is of type 4 and they are brothers (meaning they both don't belong to the spine and both are children of their infimum $u_n \wedge v_n$).

We then say that u and v are *similar* and we note $u \sim v$ if for every integer n $u_n \sim v_n$. Note that \sim is an equivalence relation on \hat{T} , and that

$$(u = v) \iff (u \sim v) \wedge (c(u) = c(v))$$

We define the mapping $\wedge : \hat{T} \times \hat{T} \rightarrow \hat{T}$ as follows: Let $u, v \in \hat{T}$. If $u \sim v$ then $u \wedge v$ is the one of u, v with smaller color; otherwise, denoting a an integer such that either $\hat{f}_a(u_a) \neq \hat{f}_a(v_a)$ or u_a and v_a are neither equal or brothers, we define $(u \wedge v)_n = u_n \wedge v_n$ if $n \geq a$, and (inductively) $(u \wedge v)_n = p_n((u \wedge v)_{n+1})$ if $n < a$.

The mapping \wedge is clearly symmetric, and it is easily checked to be measurable and associative. Let $x, y, z \in \hat{T}$. Assume there exists $i, j, k \in \mathbb{N}$ such that $x_i \not\sim y_i$, $y_j \not\sim z_j$, and $x_k \not\sim y_k$. Let $\ell = \max(i, j, k)$. Then for every $n \geq \ell$ it holds $|\{(x \wedge y)_n, (x \wedge z)_n, (y \wedge z)_n\}| \leq 2$. Hence either for every $n \in \mathbb{N}$ it holds $|\{(x \wedge y)_n, (x \wedge z)_n, (y \wedge z)_n\}| = 1$ (thus $x \wedge y = x \wedge z = y \wedge z$)

or $|\{(x \wedge y)_n, (x \wedge z)_n, (y \wedge z)_n\}| = 2$ for sufficiently large n , which implies $|\{x \wedge y, x \wedge z, y \wedge z\}| = 2$.

Otherwise, assume that there exists $i \in \mathbb{N}$ such that $x_i \not\sim y_i$, but that $y_n \sim z_n$ holds for every $n \in \mathbb{N}$. Then it is easily checked that for $n > i$ either it holds $x_n \wedge y_n = x_n \wedge z_n$, or that it holds $x_n \wedge y_n = y_n$ and $x_n \wedge z_n = z_n$. In both cases we have $|\{x \wedge y, x \wedge z, y \wedge z\}| \leq 2$.

Otherwise, $x_n \sim y_n$, $y_n \sim z_n$ and $x_n \sim z_n$ hold for every $n \in \mathbb{N}$. Then obviously $|\{x \wedge y, x \wedge z, y \wedge z\}| \leq 2$.

Altogether, according to Remark 1, it follows that $\hat{\mathbf{T}}$ is a tree-semilattice.

For $i \in \mathbb{N}$ we consider an arbitrary probability measure $\hat{\lambda}_i$ on \hat{T} with $\hat{\lambda}_i(\zeta_i^{-1}(x)) = \hat{\mu}_i(\{x\})$ for every $x \in \hat{T}_i$. As all of the p_n are measure preserving, we have that for every $n > i$ and every $x \in \hat{T}_i$ it holds

$$\begin{aligned} \hat{\lambda}_n(\zeta_i^{-1}(x)) &= \hat{\lambda}_n \circ \zeta_n^{-1} \circ p_{n-1}^{-1} \circ \cdots \circ p_i^{-1}(x) \\ &= \hat{\mu}_n \circ p_{n-1}^{-1} \circ \cdots \circ p_i^{-1}(x) \\ &= \hat{\mu}_i(\{x\}) \\ &= \hat{\lambda}_i(\zeta_i^{-1}(x)) \end{aligned}$$

As the sets $\zeta_i^{-1}(\{x\})$ (for $i \in \mathbb{N}$ and $x \in \hat{T}_i$) generate the open sets of \hat{T} , it follows that measures $\hat{\lambda}_i$ converge weakly to a probability measure $\hat{\mu}$ as i grows to infinity.

Let ϕ be a quantifier-free formula with p free variables. Let u^1, \dots, u^p be random elements of $\hat{\mathbf{T}}$ chosen independently with respect to probability measure $\hat{\mu}$. With probability at least $1 - \binom{p}{2}\epsilon_q$ no two distinct u^i 's have the same ζ_q projection and thus $\hat{\mathbf{T}}\langle u^1, \dots, u^p \rangle$ is isomorphic to $\hat{\mathbf{T}}_q\langle u_q^1, \dots, u_q^p \rangle$. As in Lemma 7, we deduce that

$$|\langle \phi, (\hat{\mathbf{T}}, \hat{\mu}) \rangle - \langle \phi, (\hat{\mathbf{T}}_q, \hat{\mu}_q) \rangle| < p^2 \epsilon_q / 2.$$

Moreover, as n grows to infinity, $\hat{\mu}_{n,q}$ converges weakly to $\hat{\mu}_q$. It follows that there exists n_0 such that for every $n \geq n_0$ it holds

$$|\langle \phi, (\hat{\mathbf{T}}_q, \hat{\mu}_q) \rangle - \langle \phi, (\hat{\mathbf{T}}_q, \hat{\mu}_{n,q}) \rangle| < \epsilon_q.$$

Also, according to Lemma 7, it holds

$$|\langle \phi, (\mathbf{T}_n, \mu_n) \rangle - \langle \phi, (\hat{\mathbf{T}}_q, \hat{\mu}_{n,q}) \rangle| < p^2 \epsilon_q / 2.$$

Thus it holds

$$|\langle \phi, (\mathbf{T}_n, \mu_n) \rangle - \langle \phi, (\hat{\mathbf{T}}, \hat{\mu}) \rangle| < (p^2 + 1) \epsilon_q.$$

Hence $(\hat{\mathbf{T}}, \hat{\mu})$ is a Borel tree-semilattice limit of the sequence $(\mathbf{T}_n, \mu_n)_{n \in \mathbb{N}}$. \square

Corollary 3. *Let (\mathbf{T}_n, μ_n) be a QF-converging sequence of uniform (finite) Borel tree-semilattices. Then there exists an atom-less limit (\mathbf{T}, μ) .*

6. APPLICATIONS: m -PARTITE COGRAPHS

A *cograph*, or *complement-reducible* graph, is a graph that can be generated from K_1 by complementations and disjoint unions. Some generalizations of cographs have been proposed; e.g., bi-cographs [13] or k -cographs [18].

A well known characterization of cographs is the following [8].

Theorem 3. *A graph G is a cograph if and only if there exists a rooted tree T (called cotree), whose set of leaves is $V(G)$, whose internal nodes are colored 0 or 1, and such that two vertices u, v are adjacent in G if and only if the color of their lowest common ancestor is 1.*

The following generalization was proposed in [12, 11]:

Definition 7 (m -partite cograph). *An m -partite cograph is a graph that admits an m -partite cotree representation, that is a rooted tree T such that*

- *the leaves of T are the vertices of G , and are colored by a label from $\{1, \dots, m\}$,*
- *the internal nodes v of T are assigned symmetric functions $f_v : \{1, \dots, m\} \times \{1, \dots, m\} \rightarrow \{0, 1\}$ with the property that two vertices x and y of G with respective colours i and j are adjacent iff their least common ancestor v in T has $f_v(i, j) = 1$.*

(This formal definition is equivalent to the intuitive one given in Section 2.) Note that cographs are exactly 1-partite cographs.

The class of cographs is random-free, as noticed by Janson [20]. The proof is based on the following characterization of random-free hereditary classes of graphs given by Lovász and Szegedy [24]. (Recall that a class \mathcal{C} is *hereditary* if every induced subgraph of a graph in \mathcal{C} is in \mathcal{C} .)

Theorem 4. *A hereditary class of graphs \mathcal{C} is random-free if and only if there exists a bipartite graph F with bipartition (V_1, V_2) such that no graph obtained from F by adding edges within V_1 and V_2 is in \mathcal{C} .*

It is well known that a cograph is a graph which does not contain the path P_4 on 4 vertices as an induced subgraph. Similarly, the class of m -partite cographs is a (well quasi-ordered) hereditary class of graphs defined by a finite number of forbidden induced subgraphs \mathcal{F}_m , one of which is the path $P_{3(2^m-1)+1}$ of length $3(2^m - 1)$ [12, 11]. This allows us to extend the result of Janson:

Lemma 10. *For every integer m , the class of all m -partite cographs is hereditary and random-free.*

Proof. That the class of m -partite cographs is hereditary is immediate from the existence of an m -partite representation, as deleting leaves in the representation gives a representation of the corresponding induced subgraph.

The path P of length $3(2^m - 1)$ is bipartite. Let (V_1, V_2) be a bipartition of its vertex set. Assume for contradiction that a graph H obtained from

P by adding edges within V_1 and V_2 is an m -partite cograph. Let Y be an m -partite cotree representation of H , and assume the laves are colored $1, \dots, m$. Recolor each leaf in V_1 by adding m to its color (c becomes $c+m$). For every internal node v , the color assigned to v corresponds to a function $f_v : \{1, \dots, m\} \times \{1, \dots, m\} \rightarrow \{0, 1\}$. Replace f_v by the function $\hat{f}_v : \{1, \dots, 2m\} \times \{1, \dots, 2m\} \rightarrow \{0, 1\}$ defined as follows: for every $1 \leq i, j \leq m$, let

$$\begin{aligned}\hat{f}_v(i, j) &= \hat{f}_v(m+i, m+j) = 0 \\ \hat{f}_v(m+i, j) &= \hat{f}_v(i, m+j) = f_v(i, j).\end{aligned}$$

Then it is easily checked that we just constructed a $2m$ -cotree representation of P , what contradicts the fact that P is not a $2m$ -partite cograph. It follows that no graph H obtained from P by adding edges within V_1 and V_2 is an m -partite cograph. Hence, according to Theorem 4, the class of all m -partite cographs is random-free. \square

It follows from Lemma 10 and results in [24] that every left-convergent sequence of m -partite cographs has a limit which is equivalent to a Borel graph excluding (as induced subgraphs) every graph in \mathcal{F}_m . Thus it holds

Proposition 1. *A Borel graph is the QF-limit of a sequence of finite m -partite cographs if and only if it excludes all the (finite) graphs in the (finite) set \mathcal{F}_m as induced subgraphs.*

In order to deal more easily with QF-limits, we consider the weighted colored tree-semilattice (\mathbf{T}, μ) corresponding to the rooted tree T , where μ is null on internal vertices of T , and uniform on the leaves of T . The interpretation $\mathbf{l}(\mathbf{T}, \mu)$ of a colored Borel tree-semilattice (\mathbf{T}, μ) is the Borel graph (G, ν) whose vertex set is the support of μ , where ν is the restriction of μ to its support, where x and y are adjacent if $\Phi(x, y)$ holds, where Φ is the quantifier-free formula asserting that for some $1 \leq i, j \leq m$ and $f \in \{0, 1\}^{\{1, \dots, m\} \times \{1, \dots, m\}}$ with $f(i, j) = 1$ it holds that x has color i , y has color j , and $x \wedge y$ has color f . Note that ν is a probability measure on the vertex set of G as the domain of \mathbf{T} is a standard Borel space (from what follows that $\mu(\text{Supp}(\mu)) = 1$).

It is easily checked that if (\mathbf{T}, μ) is the finite weighted colored tree-semilattice (\mathbf{T}, μ) corresponding to the m -partite cotree representation of a finite m -partite cograph G then $\mathbf{l}(\mathbf{T}, \mu) = G$.

It is easily checked that for every quantifier free formula ψ there exists a quantifier free formula ψ^* such that for every colored Borel tree-semilattice (\mathbf{T}, μ) it holds

$$\langle \psi, \mathbf{l}(\mathbf{T}, \mu) \rangle = \langle \psi^*, (\mathbf{T}, \mu) \rangle.$$

Theorem 5. *Limits of m -partite cographs are exactly interpretations by \mathbf{l} of atomless colored Borel tree-semilattices.*

Proof. Let $(G_n)_{n \in \mathbb{N}}$ be a left-convergent (hence QF-convergent) sequence of m -partite cographs. Let (\mathbf{T}_n, μ_n) be a colored weighted tree-semilattice such that $G_n = \mathbf{l}(\mathbf{T}_n, \mu_n)$. By compactness, there exists an increasing function $f : \mathbb{N} \rightarrow \mathbb{N}$ such that the sequence $(\mathbf{T}_{f(n)}, \mu_{f(n)})_{n \in \mathbb{N}}$ is QF-convergent. Let $(\hat{\mathbf{T}}, \mu)$ be a QF limit Borel tree-semilattice for the sequence $(\mathbf{T}_{f(n)}, \mu_{f(n)})_{n \in \mathbb{N}}$. Note that μ has no atom as $\lim_{n \rightarrow \infty} \sup_{v \in T_n} \mu_n(\{v\}) = 0$. Define the Borel graph (G, ν) as $G = \mathbf{l}(\hat{\mathbf{T}}, \mu)$. For every quantifier free formula ψ , it holds

$$\begin{aligned} \lim_{n \rightarrow \infty} \langle \psi, G_n \rangle &= \lim_{n \rightarrow \infty} \langle \psi, G_{f(n)} \rangle \\ &= \lim_{n \rightarrow \infty} \langle \psi, \mathbf{l}(\mathbf{T}_{f(n)}, \mu_{f(n)}) \rangle \\ &= \lim_{n \rightarrow \infty} \langle \psi^*, (\mathbf{T}_{f(n)}, \mu_{f(n)}) \rangle \\ &= \langle \psi^*, (\mathbf{T}, \mu) \rangle \\ &= \langle \psi, \mathbf{l}(\mathbf{T}, \mu) \rangle \end{aligned}$$

It follows that the Borel graph $\mathbf{l}(\mathbf{T}, \mu)$ is the QF-limit of the sequence $(G_n)_{n \in \mathbb{N}}$. To this Borel graph corresponds a random-free graphon, which is thus the left limit of the sequence $(G_n)_{n \in \mathbb{N}}$.

Conversely, if $G = \mathbf{l}(\hat{\mathbf{T}}, \mu)$ is the interpretation of an atomless colored Borel tree-semilattice (\mathbf{T}, μ) , then, using a construction analogous to the one use in the proof of Theorem 1, one gets that (\mathbf{T}, μ) is the QF-limit of a sequence of finite weighted colored tree-semilattices (\mathbf{T}_n, μ_n) , where μ_n is uniform on its support. Then for every integer n the interpretation $\mathbf{l}(\mathbf{T}_n, \mu_n)$ is a finite m -partite cograph (with uniform measure on its vertex set) and, as above, G is the limit of the sequence $(G_n)_{n \in \mathbb{N}}$. \square

Thus, according to Proposition 1, we get the following extension of the characterization of finite m -partite cographs:

Theorem 6. *For an atomless Borel graph G the following conditions are equivalent:*

- (1) G is the QF-limit of a sequence of finite m -partite cographs;
- (2) G is equivalent to a random-free graphon W that is the left limit of a sequence of finite m -partite cographs;
- (3) G excludes all graphs in \mathcal{F}_m as induced subgraphs;
- (4) G is the interpretation by \mathbf{l} of an atomless colored Borel tree-semilattice;

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