

# On locally-characterized expander graphs (a survey)

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## Abstract

We consider the notion of a local-characterization of an infinite family of unlabeled bounded-degree graphs. Such a local-characterization is defined in terms of a finite set of (marked) graphs yielding a generalized notion of subgraph-freeness, which extends the standard notions of induced and non-induced subgraph freeness.

We survey the work of Adler, Kohler and Peng (*32nd SODA* and *36th CCC*, 2021), which is pivoted at constructing locally-characterized expander graphs. The construction makes inherent use of the iterative and local nature of the Zig-Zag construction of Reingold, Vadhan, and Wigderson (*41st FOCS*, 2000). This yields a locally-characterizable graph property that cannot be tested (in the bounded-degree graph model) within a number of queries that does not depend on the size of the graph.

## Contents

<b>1</b>	<b>Overview</b>	<b>1</b>
<b>2</b>	<b>Background</b>	<b>2</b>
2.1	Testing in the Bounded-Degree Graph Model . . . . .	2
2.2	Generalized Subgraph Freeness Properties . . . . .	3
2.3	The Zig-Zag Product . . . . .	5
<b>3</b>	<b>On the Proof of Theorem 1.1</b>	<b>5</b>
<b>4</b>	<b>Digest and Afterthoughts</b>	<b>9</b>
	<b>Bibliography</b>	<b>10</b>

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# 1 Overview

We consider the notion of a *local-characterization* of an infinite family of unlabeled *bounded-degree* graphs. Such a local-characterization is defined in terms of a finite set of (marked) graphs yielding a generalized notion of subgraph-freeness, which extends the standard notions of induced and non-induced subgraph freeness.<sup>1</sup> Intuitively, this notion corresponds to forbidden neighbourhoods of constant distance; that is, we consider the set of graphs such that each vertex in them has a neighborhood that is not forbidden. In other words, a family of graphs  $\mathcal{G}$  is locally-characterized by a finite set of marked graphs  $\mathcal{F}$  if  $\mathcal{G}$  equals the set of  $\mathcal{F}$ -free graphs (i.e., a graph  $G$  is in  $\mathcal{G}$  if and only if for every  $F \in \mathcal{F}$  the graph  $G$  is  $F$ -free).

We stress that, for every  $\mathcal{F}$  as above, the set of  $\mathcal{F}$ -free graphs is a graph property; that is, it is closed under isomorphism. We also mention that this definition is related both to expressibility by first-order formula (cf. [1]) and to having a proximity-oblivious tester (cf. [5]). In light of this, one would expect that such graph properties would be testable (in the bounded-degree graph model) within query complexity that depends only on the proximity parameter; however, as shown by Adler, Kohler, and Peng [1], this is not the case. The latter result is proved by constructing a locally-characterizable graph property that consists solely of expander graphs (and using the fact that such a property cannot be tested within query complexity that depends only on the proximity parameter [2]). Actually, this graph property corresponds to an infinite sequence of unlabeled graphs (equiv., all  $n$ -vertex graphs that have the property are isomorphic to a single  $n$ -vertex graph).

**Theorem 1.1** (a locally-characterizable sequence of expander graphs [1]): *There exists a finite collection of marked graphs, denoted  $\mathcal{F}$ , such that the set of  $\mathcal{F}$ -free graphs is an infinite set of (bounded-degree) expander graphs. Furthermore, all  $n$ -vertex graphs that are  $\mathcal{F}$ -free are isomorphic to one another, and for some  $d \in \mathbb{N}$  and each  $m \in \mathbb{N}$  there exists an  $\Theta(d^{4m})$ -vertex  $\mathcal{F}$ -free graph.*

The proof of Theorem 1.1 is pivoted at the Zig-Zag construction of Reingold, Vadhan, and Wigderson [9]. Recall that they presented a sequence of graphs,  $(G_i)_{i \in \mathbb{N}}$ , such that  $G_1 = H^2$  for some constant-size expander  $H$  (of degree  $d$  and second-eigenvalue  $d/4$ ) and  $G_i = G_{i-1}^2 \circledast H$ , where  $\circledast$  denotes the Zig-Zag product. Furthermore, each vertex in  $G_{i-1}$  is replaced in  $G_i$  by a cloud of vertices of the same size as  $H$ , and edges of  $G_{i-1}^2$  yield “connections” between the corresponding clouds in  $G_i$  (where the edges of the Zig-Zag product correspond to three-step walks on a graph that combine these connections with copies of  $H$  that are “placed” on each cloud). Now, loosely speaking, for each  $m \in \mathbb{N}$ , the proof of Theorem 1.1 (provided in [1]) identifies a graph that consists of the graphs  $G_1, \dots, G_m$  along with edges that connect each vertex of  $G_{i-1}$  to each vertex in the corresponding cloud of  $G_i$ . In fact, the construction is first presented in terms of directed edge-colored graphs, and gadgets are later used to yield undirected graphs (with no colors).

The point is that, while it is inconceivable that we can provide a local-characterization of  $G_i$  itself, it is quite conceivable that we can provide a local-characterization of  $G_i$  in terms of  $G_{i-1}$ . Indeed, the simple relation between  $G_{i-1}$  and  $G_i$ , already capitalized by Reingold [8], is pivotal here too. Furthermore, the relation between  $G_{i-1}$  and  $G_i$  can be enforced by constraints that are independent of  $i$ . These facts are the basis for a local characterization of a graph that has  $G_1, \dots, G_m$  at its core. Needless to say, materializing this outline requires a careful implementation.

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<sup>1</sup>This notion, defined in [5], is reviewed in Section 2.2.

**Application to property testing.** We say that a property tester has size-oblivious (query) complexity if the number of queries that it makes depends only on the proximity parameter. The main result of [2] states that, in the bounded-degree graph model, every infinite property of graphs that has a tester of size-oblivious query complexity must contain an infinite hyperfinite subproperty. Recalling that hyperfinite graphs are the “extreme opposite” of expander graphs, it follows that the property asserted in Theorem 1.1 does not have a tester of size-oblivious complexity. Hence, we get

**Corollary 1.2** (a locally-characterizable property that is not testable in the bounded degree graph model within size-oblivious complexity [1]): *There exists a finite collection of marked graphs, denoted  $\mathcal{F}$ , such that the set of  $\mathcal{F}$ -free graphs does not have a tester of size-oblivious query complexity (in the bounded degree graph model). In particular, this set has no proximity-oblivious tester (in the bounded degree graph model).*

Recall that a proximity-oblivious tester is an oracle machine of constant query-complexity that accepts each graph in the property with probability 1, and rejects each graph that is not in the property with probability that is related to the (relative) distance of the graph from the property (cf. [3, Def. 1.7]). Hence, a proximity-oblivious tester for a property yields a tester of size-oblivious query complexity for that property (cf. [3, Thm. 1.9]).

**Organization.** After recalling the background (Section 2), we turn to the core of this survey (Section 3), where we provide more details on the proof of Theorem 1.1. We end with some afterthoughts (Section 4).

## 2 Background

Throughout this text, we focus on bounded-degree graphs. While the contents of Section 2.1 is well-known and may be skipped, the notion of generalized subgraph freeness (reviewed in Section 2.2) is likely to be unfamiliar to most readers. For sake of self-containment, we also review the Zig-Zag construction (in Section 2.3).

### 2.1 Testing in the Bounded-Degree Graph Model

(This model was introduced in [4] and is reviewed in [3, Chap. 9].)

The bounded-degree graph model refers to a fixed (constant) degree bound, denoted  $d \geq 2$ . In this model, a graph  $G = (V, E)$  of maximum degree  $d$  is represented by the incidence function  $g : V \times [d] \rightarrow V \cup \{\perp\}$  such that  $g(v, j) = u \in V$  if  $u$  is the  $j^{\text{th}}$  neighbor of  $v$  and  $g(v, j) = \perp \notin V$  if  $v$  has less than  $j$  neighbors.<sup>2</sup> Distance between graphs is measured in terms of their foregoing representation; that is, as the fraction of (the number of) different array entries (over  $d \cdot |V|$ ).

The tester is given oracle access to the representation of the input graph (i.e., to the incidence function  $g$ ), where for simplicity we assume that  $V = [n]$  for  $n \in \mathbb{N}$ . In addition, the tester is also given a proximity parameter  $\epsilon$  and a size parameter (i.e.,  $n$ ). Recall that graph properties are sets of graphs that are closed under isomorphism.

<sup>2</sup>For simplicity, we adopt the standard convention by which the neighbors of  $v$  appear in arbitrary order in the sequence  $(g(v, 1), \dots, g(v, \deg(v)))$ , where  $\deg(v) \stackrel{\text{def}}{=} |\{j \in [d] : g(v, j) \neq \perp\}|$ .

**Definition 2.1** (property testing in the bounded-degree graph model): For a fixed  $d \in \mathbb{N}$ , a tester for the graph property  $\Pi$  is a probabilistic oracle machine  $T$  that, on input a proximity parameter  $\epsilon > 0$  and size parameter  $n \in \mathbb{N}$ , and when given oracle access to an incidence function  $g : [n] \times [d] \rightarrow [n] \cup \{\perp\}$ , outputs a binary verdict that satisfies the following two conditions:

1. The tester accepts each graph  $G = ([n], E)$  in  $\Pi$  with probability at least  $2/3$ ; that is, for every  $g : [n] \times [d] \rightarrow [n] \cup \{\perp\}$  representing a graph in  $\Pi$  (and every  $\epsilon > 0$ ), it holds that  $\Pr[T^g(n, \epsilon) = 1] \geq 2/3$ .
2. Given  $\epsilon > 0$  and oracle access to any graph  $G$  that is  $\epsilon$ -far from  $\Pi$ , the tester rejects with probability at least  $2/3$ ; that is, for every  $g : [n] \times [d] \rightarrow [n] \cup \{\perp\}$  that represents a graph that is  $\epsilon$ -far from  $\Pi$ , it holds that  $\Pr[T^{g'}(n, \epsilon) = 0] \geq 2/3$ , where the graph represented by  $g$  is  $\epsilon$ -far from  $\Pi$  if for every  $g' : [n] \times [d] \rightarrow [n] \cup \{\perp\}$  that represents a graph in  $\Pi$  it holds that  $|\{(v, j) \in V \times [d] : g(v, j) \neq g'(v, j)\}| > \epsilon \cdot dn$ .

The tester is said to have one-sided error probability if it always accepts graphs in  $\Pi$ ; that is, for every  $g : [n] \times [d] \rightarrow [n] \cup \{\perp\}$  representing a graph in  $\Pi$  (and every  $\epsilon > 0$ ), it holds that  $\Pr[T^g(n, \epsilon) = 1] = 1$ .

The query complexity of a tester for  $\Pi$  is a function (of the parameters  $d, n$  and  $\epsilon$ ) that represents the number of queries made by the tester on the worst-case  $n$ -vertex graph of maximum degree  $d$ , when given the proximity parameter  $\epsilon$ . Fixing  $d$ , we typically ignore its effect on the complexity (equiv., treat  $d$  as a hidden constant). Our focus here is on cases in which the query complexity depends only on the proximity parameter (i.e., size-oblivious query complexity).

## 2.2 Generalized Subgraph Freeness Properties

The notion of a *generalized subgraph-freeness*, which extends the standard notions of induced and non-induced subgraph freeness, was introduced in [5]. It is aimed to capture what one can see by exploring a constant-radius neighborhood of a vertex in a graph that has some predetermined graph property. The issue is that some vertices are fully explored (i.e., the explorer sees all their neighbors), whereas for other vertices (at the boundary of the exploration) the explorer may only encounter them but not all their neighbors (since it has not traversed their incident edges).

We shall actually consider the set of subgraphs that the explorer cannot encounter when exploring a graph that has the property, where these forbidden subgraphs are represented by *marked graphs*, which are graphs in which each vertex is marked either **full** or **semi-full** or **partial**. Intuitively, the marking **full** represent a vertex that is not at the boundary of the exploration, which means that all its incident edges were traversed. In contrast, vertices at the boundary are marked as **partial**, whereas the marking **semi-full** is inessential (and is included for sake of greater flexibility (see Footnote 3)).

**Definition 2.2** (marked graphs, embedding, and generalized subgraph freeness): A marked graphs is a pair consisting of a graph and a marking of its vertices such that each vertex is marked either **full** or **semi-full** or **partial**. We say that a marked graph  $F = ([h], A)$  can be embedded in a graph  $G = ([N], E)$  if there exists a 1-1 mapping  $\phi : [h] \rightarrow [N]$  such that for every  $i \in [h]$  the following two conditions hold:

1. If  $i$  is marked **full**, then  $\phi$  yields a bijection between the set of neighbors of  $i$  in  $F$  and the set of neighbors of  $\phi(i)$  in  $G$ . That is, in this case  $\Gamma_G(\phi(i)) = \phi(\Gamma_F(i))$ , where  $\Gamma_X(v)$  denotes the set of neighbors of  $v$  in the graph  $X$ , and  $\phi(S) = \{\phi(v) : v \in S\}$ .

2. If  $i$  is marked **semi-full**, then  $\phi$  yields a bijection between the set of neighbors of  $i$  in  $F$  and the set of neighbors of  $\phi(i)$  in the subgraph of  $G$  induced by  $\phi([h])$ . That is, in this case  $\Gamma_G(\phi(i)) \cap \phi([h]) = \phi(\Gamma_F(i))$ .
3. If  $i$  is marked **partial**, then  $\phi$  yields an injection of the set of neighbors of  $i$  in  $F$  to the set of neighbors of  $\phi(i)$  in  $G$ . That is, in this case  $\Gamma_G(\phi(i)) \supseteq \phi(\Gamma_F(i))$ .

The graph  $G$  is called  $F$ -free if  $F$  cannot be embedded in  $G$  (i.e., there is no embedding of  $F$  in  $G$  that satisfies the foregoing conditions). For a set of marked graphs  $\mathcal{F}$ , a graph  $G$  is called  $\mathcal{F}$ -free if for every  $F \in \mathcal{F}$  the graph  $G$  is  $F$ -free.

Indeed, the standard notion of (non-induced) subgraph freeness is a special case of generalized subgraph freeness, obtained by considering the corresponding marked graph in which all vertices are marked **partial**. Similarly, the notion of induced subgraph freeness is a special case of generalized subgraph freeness, obtained by considering the corresponding marked graph in which all vertices are marked **semi-full**.<sup>3</sup>

Marking vertices as **full** introduces a new type of constraint; specifically, this constraint mandates the non-existence of neighbors that are outside the embedding of the marked subgraph. For example, using vertices that are marked **full**, it is possible to disallow certain degrees in the graph (see Example 2.3). Thus, the generalized notion of subgraph freeness includes properties that are not hereditary (e.g., regular graphs), whereas induced and non-induced subgraph freeness are hereditary.

**Example 2.3** (disallowing certain degrees via generalized subgraph freeness): *For every  $d' \in \{0, 1, \dots, d\}$ , we can disallow vertices of degree  $d'$  by using a  $(d' + 1)$ -vertex star in which the center is marked **full** and the  $d'$  leaves are marked **partial**.*

The foregoing example as well as the next one are actually used in the proof of Theorem 1.1. The following example refer to the case that we want to mandate that if the graph contains some fixed subgraph  $H'$  then it actually contains additional edges (i.e.,  $H \setminus H'$ ) on the same vertices.

**Example 2.4** (mandating some subgraph via generalized subgraph freeness): *Let  $H' = ([h], A')$  be a subgraph of  $H = ([h], A)$ , and suppose that we want to enforce that every induced subgraph of  $G$  that contains  $H'$  also contains  $H$ . This can be obtained by requiring  $G$  to be  $\mathcal{F}$ -free, where  $\mathcal{F}$  is the set of all marked  $h$ -vertex graphs that are consistent with  $H'$  but not with  $H$ . Specifically,  $F$  is in  $\mathcal{F}$  if  $F$  is embedded in every  $h$ -vertex graph that contains  $H'$  but not  $H$ .*

For sake of completeness, we present the following definition, which we actually use only in headings.

**Definition 2.5** (locally characterizable properties): *A graph property  $\Pi$  is called locally characterizable if there exists a finite set of marked graphs  $\mathcal{F}$  such that  $\Pi$  equals the set of  $\mathcal{F}$ -free graphs.*

(We mention that Definition [5, Def. 5.2] is more general; it allows a different set of marked graphs to be used for each graph size as long as there is a uniform bound on the size of all marked graphs used.)

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<sup>3</sup>Indeed, **semi-full** marking can be avoided by emulating marked graphs by sets of mark graphs that avoid **semi-full** marking. This is analogous to the emulation of induced subgraph freeness by non-induced subgraph freeness.

### 2.3 The Zig-Zag Product

(The Zig-Zag product was introduced and first studied in [9].)

Given a (big)  $D$ -regular graph  $G = (V, E)$ , and a (small)  $d$ -regular graph  $H = ([D], F)$ , their Zig-Zag product, denoted  $G \circledast H$ , consists of the vertex set  $V \times [D]$ , which is partitioned to  $D$ -vertex clouds such that the cloud that corresponds to vertex  $v \in V$  is the set of vertices  $C_v = \{(v, i) : i \in [D]\}$ , and edges that correspond to certain 3-step walks (as detailed next).

Actually, it is instructive to first consider the graph, denoted  $G \oplus H$ , in which copies of  $H$  are placed on the clouds (i.e., for every  $v \in V$  and  $\{i, j\} \in F$  we place the intra-cloud edge  $\{(v, i), (v, j)\}$ ), and edges of  $G$  connect the corresponding clouds by using corresponding edges; that is, if  $\{u, v\} \in E$  is the  $i^{\text{th}}$  (resp.,  $j^{\text{th}}$ ) edge incident at  $u$  (resp., at  $v$ ), then we place the inter-cloud edge  $\{(u, i), (v, j)\}$ . Note that each vertex in  $G \oplus H$  has  $d$  intra-cloud edges and a single inter-cloud edge. Now, the edges of  $G \circledast H$  correspond to 3-step walks in  $G \oplus H$  that start with an intra-cloud edge, then take the (only available) inter-cloud edge, and lastly take some intra-cloud edge; that is, such a generic walk has the form  $(v, i) \rightarrow (v, j) \rightarrow (w, k) \rightarrow (w, \ell)$ , where  $\{i, j\}, \{k, \ell\} \in F$  and  $\{(v, j), (w, k)\}$  is an inter-cloud edge in  $G \oplus H$  (i.e.,  $\{v, w\} \in E$  is the  $j^{\text{th}}$  edge incident at  $v$  and the  $k^{\text{th}}$  edge incident at  $w$ ).

We shall assume that both  $G$  and  $H$  are connected and are not bipartite. In that case, it is clear that the graph  $G \oplus H$  is also connected and non-bipartite, and it can be shown that also  $G \circledast H$  has these properties. The main technical result of [9] asserts that the convergence rate of a random walk on  $G \circledast H$  (a.k.a the relative second eigenvalue of the graph) can be upper-bounded in terms of the convergence rates of random walks on  $G$  and on  $H$ . A simple form of their bound asserts that  $\lambda(G \circledast H) \leq \lambda(G) + \lambda(H)$ , where  $\lambda(X)$  denotes the convergence rate of a random walk on the graph  $X$ . Using  $\lambda(H) \leq 1/4$ , it follows that if  $\lambda(G) \leq 1/2$ , then  $\lambda(G \circledast H) \leq 1/2$ .

## 3 On the Proof of Theorem 1.1

We shall first present a construction of a directed graph with edge-colors such that the corresponding underlying graph is an expander. This construction will be presented in terms of local conditions that the edges of the graph are required to satisfy, where the local conditions are enforced by forbidden neighborhoods of constant distance (akin those in Examples 2.3 and 2.4). Indeed, the forbidden neighborhoods correspond to directed and edge-colored versions of marked graphs, which are defined analogously to the Definition 2.2.

The main part of the construction will be directed edges that represents the edge-rotation functions of the graphs  $G_1, \dots, G_m$  in the Zig-Zag construction. Recall that the edge-rotation function of an undirected graph extend its adjacency function such that the pair  $(u, \alpha)$  is mapped to the pair  $(v, \beta)$  if the  $\alpha^{\text{th}}$  outgoing edge of  $u$  equals the  $\beta^{\text{th}}$  incoming edge of  $v$  (equiv., the  $\alpha^{\text{th}}$  port of vertex  $u$  is connected to the  $\beta^{\text{th}}$  port of vertex  $v$ ). In such a case, we shall color the directed edge  $(u, v)$  with the color  $(\alpha, \beta)$ .

Recall that  $H$  is a  $d$ -regular  $d^4$ -vertex graph and that  $G_1 = H^2$  and  $G_i = G_{i-1}^2 \circledast H$  are  $d^2$ -regular  $d^{4i}$ -vertex graphs. For every  $\alpha, \beta \in [d^2]$ , we consider the edge-set  $E_{\alpha, \beta}$  such that  $(u, v) \in E_{\alpha, \beta}$  if for some  $i$  there exists an edge in  $G_i$  that connects the  $\alpha^{\text{th}}$  port of vertex  $u$  to the  $\beta^{\text{th}}$  port of vertex  $v$ . Indeed,  $E_{\alpha, \beta}$  is viewed as a set of directed edges that are colored  $(\alpha, \beta)$ , and we *postulate* that  $(u, v) \in E_{\alpha, \beta}$  if and only if  $(v, u) \in E_{\beta, \alpha}$ . Letting  $E \stackrel{\text{def}}{=} \bigcup_{\alpha, \beta \in [d^2]} E_{\alpha, \beta}$ , we refer to  $(u, v) \in E$  as an  $E$ -edge (and to  $(u, v) \in E_{\alpha, \beta}$  as an  $E_{\alpha, \beta}$ -edge). We stress that the foregoing anti-parallel

postulate is a very minimal one and far more substantial conditions will be postulated about the  $E$ -edges by referring also to other edges that will induce a layered directed acyclic graph (with  $G_i$  identified with the  $i^{\text{th}}$  layer). Indeed, the actual structure of the graphs  $G_1, \dots, G_m$  will be enforced by relating each  $G_i$  to  $G_{i-1}$ .

As a warm-up, suppose that we want to augment the graph with auxiliary (colored) edges that will capture 2-step walks on the original graph. In such a case, we introduce, for every  $\alpha, \beta, \gamma, \delta \in [d^2]$ , an edge-set  $E'_{(\alpha,\gamma),(\delta,\beta)}$  such that  $(u, w) \in E'_{(\alpha,\gamma),(\delta,\beta)}$  if and only if there exists  $v$  such that  $(u, v) \in E_{\alpha,\beta}$  and  $(v, w) \in E_{\gamma,\delta}$ . (We stress that the latter condition is a local condition about the edge-sets  $E'_{(\alpha,\gamma),(\delta,\beta)}$ ,  $E_{\alpha,\beta}$  and  $E_{\gamma,\delta}$ ; actually, we will use  $E'$  only as a shorthand.)

As stated above, the structure of the graphs  $G_1, \dots, G_m$  is enforced by relating each  $G_i$  to  $G_{i-1}$ , where we define  $G_0$  to be the graph consisting of a single vertex. The first step in enforcing this relation is the association of vertices in  $G_{i-1}$  with clouds of vertices in  $G_i$  such that each cloud contains  $d^4$  vertices that are identified (equiv., ordered) within the cloud; that is, the  $d^4$  ports of each vertex in  $G_{i-1}^2$  are associated with distinct vertices of the corresponding cloud. This association is enforced by using edges that are directed from each vertex of  $G_{i-1}$  to the corresponding cloud of  $G_i$  such that these  $d^4$  edges are assigned different colors. Specifically, for each  $\sigma \in [d^4]$ , we introduce a set of directed edges, denoted  $P_\sigma$ , and *postulate that each vertex has at most one outgoing  $P_\sigma$ -edge and at most one incoming  $P$ -edge*, where  $P \stackrel{\text{def}}{=} \bigcup_{\sigma \in [d^4]} P_\sigma$ . Indeed,  $(u, v) \in P_\sigma$  implies that  $v$  is the  $\sigma^{\text{th}}$  vertex in the cloud associated with  $u$ , where  $u$  is the ‘‘parent’’ of  $v$  in the directed tree induced by  $P$ . Additional postulates are added to identify the vertices of  $G_0$  and  $G_m$ ; specifically:

1. Intuitively, we postulate that there exists a single vertex with no incoming  $P$ -edges; the graph  $G_0$  will consist of this vertex.

Actually, *we postulate that there exists at most one vertex with no incoming  $P$ -edges*; the existence of such a vertex will follow from the tree structure of the  $P$ -edges (see below).

2. We postulate that the  $P$ -outdegree of each vertex is either 0 or  $d^4$  (equiv., *each vertex either has no outgoing  $P$ -edges or has at least  $d^4$  outgoing  $P$ -edges*).
3. Intuitively, we postulate that all vertices that have no outgoing  $P$ -edges belong to the same  $G_i$ , and that  $i = m$ .

Actually, *we postulate that vertices that are connected by  $E$ -edges have the same number of outgoing  $P$ -edges* (equiv., the same number of outgoing  $P_\sigma$ -edges, for every  $\sigma \in [d^4]$ ). The fact that vertices with no outgoing  $P$ -edges are in  $G_m$  follows from the first item (i.e., for  $i \geq 1$ , the graph  $G_i$  cannot contain vertices with no incoming  $P$ -edges).

Combining the foregoing postulates with additional postulates that refer to  $E$ -edges, this implies that the  $P$ -edges form a directed  $d^4$ -ary tree such that all leaves are at the same distance from the root. We warn that establishing this tree structure is the most complex part of the proof of [1, Thm. 3.1].

Next, *we postulate that the  $E$ -edges between the  $d^4$  vertices that neighbor the single vertex of  $P$ -indegree 0* (i.e., the vertex of  $G_0$ ) *form a copy of  $H^2$* . Specifically, recalling that these vertices are identified by their incoming  $P$ -edges, we postulate that  $(u, v) \in E$  if and only if there exist  $\sigma, \tau \in [d^4]$  such that  $u$  (resp.,  $v$ ) has an incoming  $P_\sigma$ -edge (resp.,  $P_\tau$ -edge) from  $G_0$  and  $\{\sigma, \tau\}$  is an edge in  $H^2$ . Furthermore, in this case  $(u, v) \in E_{\alpha,\beta}$  if and only if the foregoing edge in  $H^2$  uses the  $\alpha^{\text{th}}$  port of  $u$  and the  $\beta^{\text{th}}$  port of  $v$  (for some  $\alpha, \beta \in [d^2]$ ).

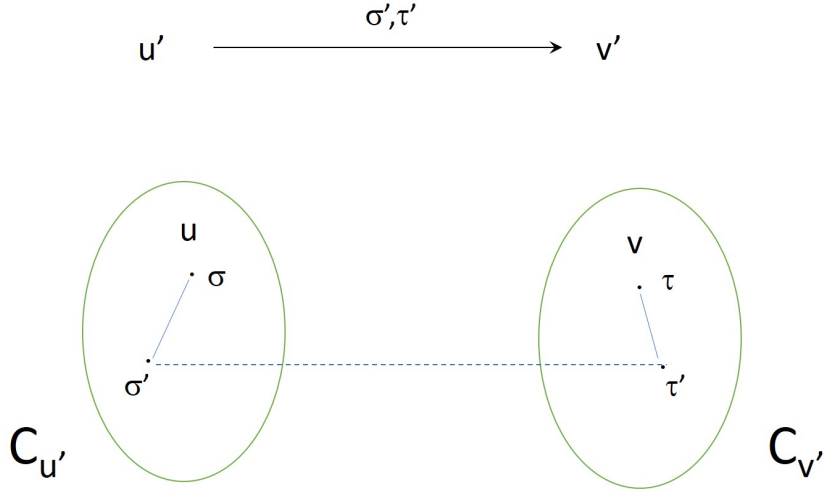


Figure 1: Vertex  $u$  (resp.,  $v$ ) is the  $\sigma^{\text{th}}$  (resp.,  $\tau^{\text{th}}$ ) vertex in the cloud  $C_{u'}$  (resp.,  $C_{v'}$ ) that replaces  $u'$  (resp.,  $v'$ ); these clouds are connected by an edge colored  $\sigma', \tau'$ .

The main issue is relating the  $E$ -edges of  $G_i = G_{i-1}^2 \otimes H$  to those of  $G_{i-1}$ , for  $i > 1$ . We stress that  $i$  itself cannot and is not referred to in this enforcement. Instead, we refer to any  $(x, y) \in E$  such that  $x$  and  $y$  have outgoing  $P$ -edges and introduce conditions on the opposite endpoints of these  $P$ -edges; that is, we mandate  $E$ -edges among  $d$  of the  $P$ -neighbors of  $x$  (which reside in the cloud that replaces  $x$ ) and  $d$  vertices of the  $P$ -neighbors of  $y$  (which reside in the cloud that replaces  $y$ ). Specifically, for  $(j, k) \in [d]^2 \equiv [d^2]$ , we postulate that  $(u, v) \in E_{(j,k),(k,j)}$  if and only if there exist  $\sigma, \tau, \sigma', \tau' \in [d^4]$  and  $(u', v') \in E'_{\sigma', \tau'}$  (i.e.,  $u'$  and  $v'$  are connected by a 2-path colored  $(\sigma', \tau')$  (see warm-up)) such that

1.  $\{\sigma, \sigma'\}$  is an edge colored  $j$  in  $H$ .
2.  $\{\tau, \tau'\}$  is an edge colored  $k$  in  $H$ .
3.  $(u', u) \in P_\sigma$  and  $(v', v) \in P_\tau$ .

(See Figure 1.) Intuitively, these conditions imply that, for some  $i$ , the  $u'$  and  $v'$  are connected in  $G_{i-1}^2$ , whereas  $u$  and  $v$  are vertices in the corresponding clouds of  $G_i$ . Furthermore,  $u$  (resp.,  $v$ ) is associated with the  $\sigma^{\text{th}}$  (resp.,  $\tau^{\text{th}}$ ) vertex of  $H$ , which in turn neighbor vertex  $\sigma'$  (resp.,  $\tau'$ ) of  $H$ . Moreover, for  $\sigma \equiv (\alpha, \gamma) \in [d^2]^2$ , vertices  $u'$  and  $v'$  are connected in  $G_{i-1}$  by a 2-path that uses the port  $\alpha \in [d^2]$  of  $u'$  and the port  $\gamma \in [d^2]$  of the intermediate vertex (whereas  $\tau' = (\delta, \beta)$  such that  $\delta$  and  $\beta$  are the ports used in walking this 2-path in the opposite direction). Indeed, the 2-paths referred to here are the edges of  $E' \stackrel{\text{def}}{=} \bigcup_{\sigma', \tau' \in [d^4]} E'_{\sigma', \tau'}$ , which were defined in the warm-up.

The foregoing description suggests that the  $P$ -edges of a graph that satisfies the listed postulates form a  $d^4$ -ary directed tree such that all leaves are at the same distance from the root, and that the subgraph (of  $E$ -edges) induced by the set of vertices that are at distance  $i$  from the root equals  $G_i$ . This is indeed the case, but proving the former fact (which refers to the  $P$ -edges) requires using



also the postulates that refer to the  $E$ -edges.<sup>4</sup> This is core of the analysis provided in [1, Sec. 3.1]. Hence, we have

**Lemma 3.1** (the postulated conditions determine a unique unlabeled directed  $n$ -vertex graph): *For  $n = \sum_{i=0}^m d^{4i}$ , an  $n$ -vertex (unlabeled edge-colored) directed graph satisfies the foregoing conditions<sup>5</sup> if and only if it consists of the graphs  $G_0, G_1, \dots, G_m$  (such that  $G_1 = H^2$  and  $G_i = G_{i-1}^2 \otimes H$ ) that are connected by  $P$ -edges as outlined above (i.e., each vertex in  $G_{i-1}$  is connected by an  $P_\sigma$ -edge to the  $\sigma^{\text{th}}$  vertex in the corresponding cloud of  $G_i$ ). If  $n > 1$  is not of the foregoing form, then no  $n$ -vertex graph satisfies these conditions.*

We note that the foregoing conditions can be enforced by forbidden neighborhoods of constant distance (akin those in Examples 2.3 and 2.4). Indeed, the forbidden neighborhoods correspond to directed and edge-colored versions of marked graphs, which are defined analogously to the Definition 2.2.

The foregoing  $n$ -vertex graph (consisting of  $G_0, G_1, \dots, G_m$  and the  $P$ -edges) has constant degree. We also observe that the corresponding undirected graph is an expander, by using the combinatorial notion of expansion. This is the case because each of the  $G_i$ 's is an expander, whereas each vertex in  $G_{i-1}$  is connected to  $d^4$  different vertices in  $G_i$ . Hence, for every set of vertices  $S$  and each  $i$ , letting  $S_i$  denote the vertices of  $S$  that reside in the  $d^{4i}$ -vertex graph  $G_i$ , we observe that if  $|S_{i-1}| \leq d^{4(i-1)}/2$  then  $S_{i-1}$  contributes to the expansion inside  $G_{i-1}$  and otherwise  $S_{i-1}$  neighbors  $d^4 \cdot |S_{i-1}| > d^{4i}/2$  vertices in  $G_i$ .

Lastly, we observe that the foregoing construction can be converted to the context of (simple) undirected graphs (with no edge-colors). This is done by replacing each color class and edge-direction by a different asymmetric gadget such that the gadgets are non-isomorphic and their vertices can be distinguished from the original ones. In particular, we may use gadgets that contain vertices of higher degree than the degree of the original vertices. The same transformation is applied

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<sup>4</sup>Specially, the postulates that refer to  $P$ -edges only enforce that the corresponding graph consists of at most one directed tree and a collection of directed cycles such that each vertex on each cycle is a root of a directed tree. However, the postulates that refer to  $E$ -edges imply that no such cycles exist, and so the graph consists of a single directed tree.

<sup>5</sup>Following is a compilation of all the conditions.

- *The edge-rotation* (i.e., anti-parallel) *condition*:  $(u, v) \in E_{\alpha, \beta}$  if and only if  $(v, u) \in E_{\beta, \alpha}$
- *The parental* (i.e.,  $P$ -edges) *conditions*:
  - For every  $\sigma \in [d^4]$  and every  $u$ , there exists at most one  $v$  such that  $(u, v) \in P_\sigma$ .
  - For every  $v$ , there exists at most one  $u$  such that  $(u, v) \in P$ .
  - There exists at most one  $v$  such that for every  $u$  it holds that  $(u, v) \notin P$ .
  - For every  $u$ , the set  $\{v : (u, v) \in P\}$  is either empty or has size  $d^4$ , where in the latter case for every  $\sigma \in [d^4]$  there exists a unique  $v$  such that  $(u, v) \in P_\sigma$ .
  - For every  $(u, u') \in E$  it holds that  $|\{v : (u, v) \in P\}| = |\{v' : (u', v') \in P\}|$ .
- *The base graph* (“level one”) *condition*: Let  $r$  denote the vertex that has no incoming  $P$ -edges, and  $v_\sigma$  be such that  $(r, v_\sigma) \in P_\sigma$  (for  $\sigma \in [d^4]$ ). Then,  $(v_\sigma, v_\tau) \in E_{(j,k), (k,j)}$  if and only if there exists  $\rho \in [d^4]$  such that  $\{\sigma, \rho\}$  is an edge colored  $j$  in  $H$  and  $\{\rho, \tau\}$  is an edge colored  $k$  in  $H$ .
- *The Zig-Zag condition*: For  $(j, k) \in [d]^2 \equiv [d^2]$ , we postulate that  $(u, v) \in E_{(j,k), (k,j)}$  if and only if there exist  $\sigma, \tau, \sigma', \tau' \in [d^4]$  and  $(u', v') \in E_{\sigma', \tau'}$  (i.e.,  $u'$  and  $v'$  are connected by a 2-path colored  $(\sigma', \tau')$  (see warm-up)) such that  $\{\sigma, \sigma'\}$  is an edge colored  $j$  in  $H$ ,  $\{\tau, \tau'\}$  is an edge colored  $k$  in  $H$ ,  $(u', u) \in P_\sigma$ , and  $(v', v) \in P_\tau$ .

to the (directed and edge-colored) forbidden neighborhoods that enforce the conditions imposed on the (directed and edge-colored) construction. This yields a corresponding finite set of marked graphs, denoted  $\mathcal{F}$ , that satisfies the following –

**Proposition 3.2** (a locally-characterizable property of expander graphs): *The set of  $\mathcal{F}$ -free graphs is an infinite set of expander graphs. Furthermore, this set contains a single unlabeled  $\Theta(d^{4m})$ -vertex graph for every  $m \in \mathbb{N}$ .*

We mention that, by using additional constraints, one can force these expanders to be regular graphs. In fact, this is done in [1].

## 4 Digest and Afterthoughts

The proof of Lemma 3.1 does not refer to the fact that  $H$  and the  $G_i$ 's are expanders. It actually uses only the fact that each of the  $G_i$ 's is a connected graph and that  $G_i$  is derived from  $G_{i-1}$  by replacing vertices with clouds and replacing edges with specific bipartite graphs between the corresponding clouds. Specifically, the  $\sigma^{\text{th}}$  vertex of the cloud of  $u'$  is connected in  $G_i$  to the  $\tau^{\text{th}}$  vertex of the cloud of  $v'$  if and only if  $u'$  and  $v'$  are connected in  $G_{i-1}^2$  via ports  $\sigma'$  and  $\tau'$  respectively, and some condition regarding  $\sigma, \tau, \sigma', \tau' \in [d^4]$  holds. Hence, Lemma 3.1 remains valid also when replacing the recursion  $G_i = G_{i-1}^2 \otimes H$  by the recursion  $G_i = f(G_{i-1})$ , provided that  $f$  satisfies the following conditions:

1. For some constant  $c > 1$ , each vertex of  $G'$  is mapped to a cloud of  $c$  vertices in  $G = f(G')$ , and the vertices of these clouds are ordered (equiv., identified by indices in  $[c]$ ).

We stress that each vertex of  $G$  belongs to a single cloud.

2. If  $G'$  is connected, then so is  $G = f(G')$ .
3. Let  $u$  and  $v$  be vertices in  $G$  such that  $u$  (resp.,  $v$ ) is the  $\sigma^{\text{th}}$  vertex of the cloud  $u'$  (resp., the  $\tau^{\text{th}}$  vertex of the cloud  $v'$ ). Then, there exists an edge between the  $\alpha^{\text{th}}$  port of  $u$  and the  $\beta^{\text{th}}$  port of  $v$  if and only if the (unlabeled) constant-distance neighborhoods of  $u'$  and  $v'$  (in  $G'$ ) satisfy a condition that depends on  $\sigma, \tau, \alpha$  and  $\beta$  only. (The condition may refer to the port indices of additional vertices in  $G'$ , but not to the labels of these vertices.)

In addition,  $G_1$  may be an arbitrary constant-sized connected graph; if the number of vertices in  $G_1$  is different from  $c$ , then the postulate regarding the outgoing  $P$ -edges of the root of the  $P$ -tree should be revised accordingly (i.e., the root of the  $P$ -tree would have a different degree (which matches  $G_1$ ) than all internal vertices in the tree (which still have degree  $c$ )).

Note that the construction schema outlined above (which yields a graph consisting of  $G_0, G_1, \dots, G_m$  and  $P$ -edges from vertices of  $G_{i-1}$  to the corresponding clouds of  $G_i$ ) always yields graphs of logarithmic diameter (by virtue of the  $P$ -edges). In Section 3, we used  $G_1 = H^2$  and  $f(G) = G^2 \otimes H$ , for some  $c$ -vertex graph  $H$  (i.e.,  $H$  is a sufficiently strong  $d$ -regular expander and  $c = d^4$ ). These specific choices were important only for asserting that the  $G_i$ 's are (bounded-degree) expanders, which was important for Proposition 3.2 and Corollary 1.2. Before turning to Corollary 1.2, we present a couple of other incarnations of this construction schema.

**Example 4.1** (using arbitrary  $d$ -regular connected graphs): For any  $d \geq 2$  and  $t \geq 1$ , let  $G_1$  be an arbitrary  $(d+1)$ -regular connected graph, and  $H$  be an arbitrary connected  $(d+1)^t$ -vertex  $d$ -regular graph. In particular, for  $d = 2$  the graph  $H$  is a  $3^t$ -cycle, whereas for  $t = 1$  the graph  $H$  is a  $(d+1)$ -clique. Then, for any  $(d+1)$ -regular graph  $G$ , letting  $f(G) = G^t \textcircled{\text{R}} H$ , where  $\textcircled{\text{R}}$  denotes the replacement product (outlined in Section 2.3), satisfies the foregoing conditions.

We stress that Example 4.1 makes sense even for  $d = 2$  and  $t = 1$ . More importantly, for adequate choice of  $d, H$  and  $G_1$ , even for  $t = 3$ , the corresponding  $G_i$ 's are expanders, and so the graph resulting from the construction schema is an expander.<sup>6</sup>

**Example 4.2** (using arbitrary  $d$ -regular connected graphs, take 2): For any  $d \geq 3$ , let  $G_1$  be an arbitrary  $d$ -regular connected graph, and  $H$  be an arbitrary connected  $h$ -vertex graph with  $h - d$  vertices of degree  $d$  and  $d$  vertices of degree  $d - 1$ . In particular,  $H$  can be obtained by omitting a single vertex from a  $d$ -regular  $(h+1)$ -vertex graph. For any  $d$ -regular graph  $G$ , let  $G \textcircled{\text{R}} H$  denote a version of the replacement product in which only the low degree vertices of  $H$  are used as ports of inter-cloud edges. Then, letting  $f(G) = G \textcircled{\text{R}} H$ , for any  $d$ -regular graph  $G$ , satisfies the foregoing conditions.

Observe that for any admissible choice of  $d, H$  and  $G_1$ , the graph resulting from the construction schema is an hyperfinite.<sup>7</sup> This implies that the corresponding graph property is testable within size-oblivious complexity (see [7]).

Turning to Corollary 1.2, we recall that it was proved by combining Proposition 3.2 with the fact that the corresponding graph property (which contains only expander graphs) does not contain an infinite hyperfinite subproperty, and so cannot have a tester of size-oblivious query complexity [2]. It is quite conceivable that Corollary 1.2 can be proved also without relying on [2]. Specifically, a potential tester of size-oblivious query complexity for the graph property that corresponds to Lemma 3.1 cannot query most  $G_i$ 's, and so it may not be able to detect a mismatch between  $G_i$  and  $G_{i-1}$  for a random  $i \in [m]$ . This intuition must refer to some feature of the function  $f$ . In addition, it should be established that such a mismatch yields a graph that is far from the property. Needless to say, Example 4.2 has to be avoided.

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<sup>6</sup>We use  $\lambda(G \textcircled{\text{R}} H) \leq 1 - \frac{(1-\lambda(H)^2) \cdot (1-\lambda(G))}{2}$  (see [6, Thm. 9.1 (iii)] and the comment at the bottom of [6, p. 510]).

<sup>7</sup>That is, for every  $\epsilon > 0$ , omitting an  $\epsilon$  fraction of the edges of the graph (which consists of  $G_0, G_1, \dots, G_m$  and the  $P$ -edges) yields a graph with connected components of size  $O(1/\epsilon)$ . Specifically, letting  $\ell = \log_h(1/\epsilon) + O(1)$ , this can be done by omitting all edges that are incidence at vertices in  $G_0, G_1, \dots, G_{m-\ell}$  (i.e., replacing these graphs by isolated vertices) and replacing  $G_{m-\ell+1}, \dots, G_m$  with  $G'_{m-\ell+1}, \dots, G'_m$  such that  $G'_{m-\ell+i} = G'_{m-\ell+i-1} \textcircled{\text{R}} H$  for every  $i \in [\ell - 1]$ . In other words, the only remaining edges are those that have both endpoints in  $G'_{m-\ell+1}, \dots, G'_m$ , whereas  $G'_{m-\ell+1}$  consists of isolated copies of  $H$ . Thus, these edges are internal to the  $(\sum_{i \in [\ell]} h^i)$ -sized connected components that replace vertices of  $G_{m-\ell}$ .

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