THEORY OF COMPUTING, Volume 1 (2005), pp. 177–216
http://theoryofcomputing.org

Linear Equations, Arithmetic Progressions, and Hypergraph Property Testing

Noga Alon* Asaf Shapira†

Received: January 12, 2005; published: October 12, 2005.

Abstract: For a fixed k-uniform hypergraph D (k-graph for short, $k \geq 3$), we say that a k-graph H satisfies property $\mathcal{P}_D$ (or property $\mathcal{P}^*_D$) if it contains no copy (or no induced copy) of D. Our goal in this paper is to classify the k-graphs D for which there are property-testers for testing $\mathcal{P}_D$ and $\mathcal{P}^*_D$ whose query complexity is polynomial in $1/\varepsilon$. For such k-graphs we say that property $\mathcal{P}_D$ (or property $\mathcal{P}^*_D$) is *easily testable*.

For $\mathcal{P}^*_D$, we prove that aside from a single 3-graph, $\mathcal{P}^*_D$ is easily testable **if and only if** D is a single k-edge. We further show that for large k, one can use more sophisticated techniques in order to obtain better lower bounds for any large enough k-graph. These results extend and improve the authors' previous results about graphs (SODA 2004) and results by Kohayakawa, Nagle and Rödl on k-graphs (ICALP 2002).

For $\mathcal{P}_D$, we show that for any k-partite k-graph D, property $\mathcal{P}_D$ is easily testable. This is established by giving an efficient one-sided-error property-tester for $\mathcal{P}_D$, which improves the one obtained by Kohayakawa et al. We further prove a nearly matching lower bound

*Supported in part by a USA-Israeli BSF grant, by the Israel Science Foundation and by the Hermann Minkowski Minerva Center for Geometry at Tel Aviv University.

†Supported in part by a Charles Clore Foundation Fellowship and by an IBM Ph. D. Fellowship.

ACM Classification: G.2.2, F.2.2

AMS Classification: 05C65, 68R10

Key words and phrases: Property Testing, Hypergraphs, Lower Bounds, Additive Number Theory, Linear Algebra, Extremal Problems

 DOI: 10.4086/toc.2005.v001a009

on the query complexity of such a property-tester. Finally, we give a sufficient condition for inferring that $\mathcal{P}_D$ is not easily testable. Though our results do not supply a complete characterization of the k-graphs for which $\mathcal{P}_D$ is easily testable, they are a natural extension of the previous results about graphs (Alon, 2002).

Our proofs combine results and arguments from additive number theory, linear algebra, and extremal hypergraph theory. We also develop new techniques, which we believe are of independent interest. The first is a construction of a dense set of integers which does not contain a subset that satisfies a certain set of linear equations. The second is an algebraic construction of certain extremal hypergraphs. These techniques have already been applied in two papers under publication by the authors.

1 Introduction

1.1 Definitions

All the hypergraphs considered here are finite and have no parallel edges. A *k-uniform* hypergraph (or *k-graph*, for short) $H = (V,E)$, is a hypergraph in which each edge contains precisely k distinct vertices of V. As usual, a 2-graph may be referred to simply as a graph. Let $\mathcal{P}$ be a property of k-graphs, that is, a family of k-graphs closed under isomorphism. A k-graph H with n vertices is *ε-far from satisfying* $\mathcal{P}$ if one must add or delete at least εn^k edges in order to turn H into a k-graph satisfying $\mathcal{P}$. An *ε-tester*, or *property-tester*, for $\mathcal{P}$ is a randomized algorithm which, given the quantity n and the ability to make queries whether a desired set of k vertices spans an edge in H, distinguishes with high probability (say, 2/3) between the case of H satisfying $\mathcal{P}$ and the case of H being ε-far from satisfying $\mathcal{P}$. Such an ε-tester is said to have *one-sided* error if when H satisfies $\mathcal{P}$ it determines that this is the case (with probability 1). The ε-tester is said to have *two-sided* error if it may err in both direction, namely if it has nonzero probability of accepting k-graphs that are ε-far from satisfying $\mathcal{P}$, as well as nonzero probability of rejecting k-graphs that satisfy $\mathcal{P}$. The property $\mathcal{P}$ is called *strongly-testable* if, for every fixed $\varepsilon > 0$, there exists a one-sided ε-tester for $\mathcal{P}$ whose total number of queries is bounded only by a function of ε that is independent of the size of the input k-graph. This means that the running time of the algorithm is also bounded by a function of ε only, and is independent of the input size. In this paper we measure query-complexity by the number of vertices sampled, assuming we always examine all edges spanned by them. For a fixed k-graph D, let $\mathcal{P}^*_D$ denote the property of being induced D-free. Therefore, H satisfies $\mathcal{P}^*_D$ if and only if it contains no induced sub-hypergraph isomorphic to D. We define $\mathcal{P}_D$ to be the property of being (not necessarily induced) D-free. Therefore, H satisfies $\mathcal{P}_D$ if and only if it contains no copy of D.

The general notion of property testing was first formulated by Rubinfeld and Sudan [24], who were motivated mainly by its connection to the study of program checking. The study of the notion of testability for combinatorial objects, and mainly for labeled graphs, was introduced by Goldreich, Goldwasser and Ron [13]. See [11] and [23] for surveys and additional references on the topic.

1.2 Previous results

In [3] it is shown that every first order graph property without a quantifier alternation of type "$\forall\exists$" has ε-testers whose query complexity is independent of the size of the input graph. It follows from the main result of [3] that, for every fixed graph D, the property $\mathcal{P}^*_D$ is strongly testable. Although the query complexity is independent of n, it has a huge dependency on $1/\varepsilon$ (the fourth function in the Ackermann Hierarchy, which is a tower of towers of exponents of height polynomial in $1/\varepsilon$). In [2] it was shown, using Szemerédi's Regularity Lemma, that, for every fixed graph D, the property $\mathcal{P}_D$ is also strongly testable. This result was generalized to the case of directed graphs (digraphs) in [5], by first proving a directed version of the regularity lemma. In the above two cases the query complexity is also huge, a tower of 2's of height polynomial in $1/\varepsilon$.

As in many cases, moving from graphs to hypergraphs has many unexpected difficulties. While for graphs the strong testability of $\mathcal{P}_D$ and $\mathcal{P}^*_D$ follows quite easily from an appropriate regularity lemma [3, 27], until very recently there was no strong enough regularity lemma suitable for proving that $\mathcal{P}_D$ and $\mathcal{P}^*_D$ are strongly testable for any k-graph D. The only results for k-graphs were obtained by Frankl and Rödl [12], who (implicitly) showed that, for any 3-graph D, property $\mathcal{P}_D$ is strongly testable (see also [19]) and by Kohayakawa, Nagle and Rödl in [17], where it was shown that, for any 3-graph D, property $\mathcal{P}^*_D$ is strongly testable. Recent works of Gowers [15] and independently of Nagle, Rödl, Schacht and Skokan [22, 20] suggest that a powerful new hypergraph regularity lemma implies that $\mathcal{P}^*_D$ and $\mathcal{P}_D$ are both strongly testable for any k-graph D, for arbitrary value of k. It should be noted, however, that the upper bounds that these new techniques may guarantee, for testing k-uniform hypergraphs, will probably belong to the k^{th} level of the Ackermann Hierarchy.

For some k-graphs, however, there are obviously much more efficient property-testers than the ones guaranteed by the general results described above. For example, for any k, if D is a single k-edge, then there is obviously a one-sided-error property-tester for $\mathcal{P}_D = \mathcal{P}^*_D$, whose query complexity is $\Theta(1/\varepsilon)$. We simply sample $\Theta(1/\varepsilon)$ vertices, and check if they span an edge. A natural question is, therefore, to decide for which k-graphs D there is a one-sided-error property-tester for $\mathcal{P}_D$ or $\mathcal{P}^*_D$ whose query complexity is bounded by a *polynomial* of $1/\varepsilon$. We introduce the following definition:

Definition 1.1 (Easily Testable). A property $\mathcal{P}$ is *easily testable* if there is a one-sided-error property-tester for $\mathcal{P}$ whose query complexity is polynomial in $1/\varepsilon$.

In [1] it is shown that for an undirected graph D, property $\mathcal{P}_D$ is easily testable if and only if D is bipartite. One of the main results of [5] is a precise characterization of all the directed graphs D for which $\mathcal{P}_D$ is easily testable. In [4] it is shown that for any graph D other than the paths of length 1, 2, 3 (which have 2,3,4 vertices respectively), the cycle of length 4, and their complements, $\mathcal{P}^*_D$ is not easily testable. A similar result was also proved for directed graphs. For $k > 2$, the only result in the direction of classifying the k-graphs for which $\mathcal{P}_D$ and $\mathcal{P}^*_D$ are easily testable was obtained in [17], where it was shown that for any k, the complete k-graph on $k+1$ vertices is not easily testable. A natural step is therefore to classify all the k-graphs D for which $\mathcal{P}^*_D$ and $\mathcal{P}_D$ are easily testable.

1.3 The new results

Our first two results concern testing $\mathcal{P}^*_D$. In what follows we denote by $D_{3,2}$ the unique 3-graph on 4-vertices that has 2 edges.

Theorem 1.2. *For any $k \geq 3$ and any k-graph D other than a single k-edge and $D_{3,2}$, there exists a constant $c = c(D) > 0$ such that the query-complexity of any one-sided-error ε-tester for $\mathcal{P}^*_D$ is at least*

$$\left(\frac{1}{\varepsilon}\right)^{c\log(1/\varepsilon)} .$$

As noted above, for any k, there is an obvious one-sided-error property-tester for the case of D being a single k-edge, whose query complexity is $\Theta(1/\varepsilon)$. We therefore get that Theorem 1.2 gives a complete characterization of the k-graphs D for which $\mathcal{P}^*_D$ is easily testable, besides the case of $D_{3,2}$.

Our second result states that for large k we can significantly improve the lower bounds for testing $\mathcal{P}^*_D$, for almost all k-graphs.

Theorem 1.3. *For any k there is a constant $r(k)$ such that, for any k-graph D on at least $r(k)$ vertices, there is a constant $c = c(D) > 0$ such that any one-sided-error property-tester for testing $\mathcal{P}^*_D$ has query complexity at least*

$$\left(\frac{1}{\varepsilon}\right)^{c(\log 1/\varepsilon)^{\lfloor \log k \rfloor}} .$$

In fact, the lower bounds in the above theorem apply also to some k-graphs on less than $r(k)$ vertices, amongst them all the k-graphs that contain F^k, which is the complete k-graph on $k+1$ vertices. As a special case, we thus improve the lower bound for the case of F^k obtained in [17], which was similar to the lower bound in Theorem 1.2. Moreover, our technique supplies a slightly inferior lower bound (namely, with exponent $\lfloor \log \lceil k/2+1 \rceil \rfloor$ instead of $\lfloor \log k \rfloor$) for **any** k-graph D on more than k vertices (see discussion following the proof of Theorem 1.3 in Section 5.2). Note that the bounds of Theorem 1.3 are *super-polynomial* in the bounds of Theorem 1.2; thus for large k we obtain substantially better lower bounds.

Our next two results concern testing $\mathcal{P}_D$. We first give an efficient one-sided-error property-tester for any k-partite k-graph. Recall that a k-graph is k-partite if its vertex set can be partitioned into k sets such that each edge has precisely one vertex in each of the partition classes.

Theorem 1.4. *(i) Let $t_1 \leq \ldots \leq t_k$, put $t^* = t_1 \cdot \ldots \cdot t_k$, and let D be any k-partite k-graph with partition classes of sizes $t_1, \ldots, t_k$. Then there is a one-sided-error ε-tester for $\mathcal{P}_D$ with query complexity*

$$O\left(\frac{1}{\varepsilon}\right)^{t^*/t_k} .$$

(ii) For any k-partite k-graph D on d vertices which contains $|E|$ edges, the query complexity of any one-sided-error ε-tester for $\mathcal{P}_D$ is

$$\Omega\left(\frac{1}{\varepsilon}\right)^{|E|/d} .$$

The upper bound in the above theorem improves the one obtained by [17] in which the exponent was t^*. See Section 7 for more details. Observe that when D is the complete k-partite k-graph $K_{t,\dots,t}$, the exponent in the upper bound is t^{k-1} while the one in the lower bound is t^{k-1}/k, which is quite close. The proof of this theorem appears in Section 7.

For the next result we need some definitions. A *homomorphism* from a k-graph D to a k-graph K is a mapping $\varphi : V(D) \to V(K)$ which maps edges to edges, namely, if $(v_1,\dots,v_k) \in E(D)$ then $(\varphi(v_1),\dots,\varphi(v_k)) \in E(K)$.

Definition 1.5. **(Core)** The *core* of a k-graph D is the smallest (in terms of edges) **sub-hypergraph** of D, denoted K, for which there exists a homomorphism from D to K. A k-graph D is called a core if it is the core of itself.

We also need to define a generalization of cycles in graphs;

Definition 1.6. **(Hyper-Cycle[1])** A k-graph on d vertices $1,\dots,d$ is called a *hyper-cycle* if it contains $d-k+2$ edges $e_1,\dots,e_{d-k+2}$ and one can arrange its vertices on a cycle such that every edge e_i contains the vertices $\{i \pmod d,\dots,i+k-1 \pmod d\}$.

Observe that for $k=2$ the above definition boils down to the definition of a cycle. Also, a single k-edge is not a hyper-cycle, as it contains $1 < k-k+2 = 2$ edges. The next theorem gives a sufficient condition for inferring that for a k-graph D, property $\mathcal{P}_D$ is not easily testable.

Theorem 1.7. *If the core of a k-graph D contains a hyper-cycle, then there exists a constant $c = c(D) > 0$ such that the query-complexity of any one-sided-error ε-tester for $\mathcal{P}_D$ is at least*

$$\left(\frac{1}{\varepsilon}\right)^{c\log(1/\varepsilon)} .$$

Observe that the core of any k-partite k-graph is a single edge, which does not satisfy the definition of a hyper-cycle. It is important to note that though Theorem 1.7 establishes that for a large family of non-k-partite k-graphs D, property $\mathcal{P}_D$ is not easily testable, it does not cover all the non k-partite k-graphs, as the core of some of them does not contain a hyper-cycle. However, for $k=2$, Theorem 1.7 does cover all the non-bipartite graphs, as it is easy to see that the core of any non-bipartite graph must contain a cycle, namely, one of the shortest odd cycles of the graph. As we have mentioned above, for $k=2$, this is precisely the definition of a hyper-cycle. Hence, Theorem 1.4 and Theorem 1.7 imply that for $k=2$, property $\mathcal{P}_D$ is easily testable if and only if D is bipartite, thus extending the result of [1], where the characterization for graphs was first obtained. We finally mention that using the main ideas of the proof of Theorem 1.7 one can slightly extend it by showing that it holds even if in the definition of a hyper-cycle one only requires that the first two vertices of e_i would be $i \pmod d, i+1 \pmod d$ (its other vertices lying in $\{1,2,\dots,d\}$).

As the proof with this definition is more involved (mainly due to cumbersome notations), and still does not cover all the cases of non-k-partite k-graphs, we preferred to give the proof of the slightly less general case, which contains all the important ideas.

[1] In some papers on hypergraphs this object is called a *tight cycle*.

We have thus far considered only one-sided-error property-testers. A natural question is if there are k-graphs $\mathcal{D}$, for which $\mathcal{P}^*_D$ (or $\mathcal{P}_D$) is not easily testable, but can still be tested with two-sided error and query complexity polynomial in $1/\varepsilon$. We can (partially) rule out this possibility by showing that the lower bounds of Theorem 1.2, Theorem 1.3 and Theorem 1.7 can all be extended to the case of two-sided-error ε-testers.

Theorem 1.8. *The lower bounds of Theorem 1.2, Theorem 1.3 and Theorem 1.7 hold for two-sided-error ε-testers as well.*

1.4 Techniques

Our main results in this paper, Theorem 1.2, Theorem 1.3 and Theorem 1.7, are based on two new constructions. All the previous results on testing $\mathcal{P}_D$ and $\mathcal{P}^*_D$ ([1, 5, 4, 17]) were based on constructions of sets of integers which do not contain small subsets that satisfy a certain *single* equation. All these constructions were based on Behrend's construction [7] of a large set of integers containing no 3-term arithmetic progression. In our case, however, we consider sets of integers that do not contain small subsets that satisfy a certain *set* of equations. The key benefit of this consideration is that requiring the set of integers to satisfy a set of equations, rather than a single one, allows us to construct much denser sets than the ones used in previous papers. This benefit translates to significantly improved lower bounds. The proof of this new construction appears in Section 2. Some of the techniques we apply in the proof of this result are motivated by the work of Laba and Lacey [18], where they reproved a result of Rankin [21] by constructing large sets of integers without k-term arithmetic progressions. The ideas used in our number-theoretic construction have been further applied in another recent paper [26].

Our second technical contribution is an algebraic construction of certain extremal k-graphs. The goal of this construction is to resolve the main technical difficulty in the proof of the main results. The main benefit of this construction is that it allows us to infer certain linear equations between the integers that are used in the definition of these k-graphs. In previous papers about testing subgraphs in graphs, ([1, 5, 4]) inferring these linear equations was trivial. This construction can be viewed as an extension of a construction of Frankl and Rödl [12] (which is an extension of the well known construction of Ruzsa and Szemerédi [25]), but ours is far more complicated to analyze. It is also much more applicable than the construction of [12], which, for example, can only be used to show that the complete k-graph on $k+1$ vertices is not easily testable and with a lower bound as in Theorem 1.2, rather than the one in Theorem 1.3. Our new algebraic technique is applied in Section 3 and Section 6. The ideas used in the algebraic construction of extremal k-graphs have been further applied in another recent paper [6].

1.5 Organization

In Section 2 and Section 3 we develop the main machinery needed to prove Theorem 1.2 and Theorem 1.3. In Section 2 we describe a new number-theoretic construction. In Section 3 we describe a new algebraic construction of extremal k-graphs. In Section 4 we prove two useful lemmas, which use the constructions of Section 2 and Section 3 in order to obtain the lower bounds of Theorem 1.2 and Theorem 1.3. The results of Section 2, Section 3 and Section 4 are essentially independent, and thus these sections can be read independently. To further simplify the reading of these sections, each of them starts with a short subsection in which we state the important definitions and state the main results proved in that section.

The proofs of Theorem 1.2 and Theorem 1.3, which follow quite easily by combining the main results of Section 2, Section 3 and Section 4, are given in Section 5. In Section 6 we apply our algebraic technique again, this time to construct extremal k-graphs, which are a central tool in the proof of Theorem 1.7. The proof of Theorem 1.7 also appears in Section 6. In Section 7 we prove Theorem 1.4. As the proof of Theorem 1.8 uses ideas similar to the ones used in [4] (in addition to the ideas of this paper) we omit it. Section 8 contains some concluding remarks and open problems.

Throughout this paper we assume, whenever this is needed, that the error parameter ε is sufficiently small, and that the number of vertices n of the k-graph considered is sufficiently large compared to $1/\varepsilon$. In order to simplify the presentation, we omit all floor and ceiling signs whenever these are not crucial, and make no attempt to optimize the absolute constants. All the logarithms appearing in the paper are in base 2.

2 Arithmetic Progressions and Linear Equations

2.1 The main results of this section

In this section we give our number-theoretic construction, which will be later used in Section 5. We start with some definitions.

Definition 2.1. **((k,h)-Gadget)** Call a set of $k-2$ linear equations $\mathcal{E} = \{e_1, \dots, e_{k-2}\}$ with integer coefficients in k unknowns $x_1, \dots, x_k$ a (k,h)-*gadget* if it satisfies the following properties:

1. Each of the unknowns $x_1, \dots, x_k$ appears in at least one of the equations.
2. For $1 \le t \le k-2$ equation e_t is of the form
$$p_t x_i + q_t x_j = (p_t + q_t) x_\ell \quad ,$$
where $0 < p_t, q_t \le h$ and x_i, x_j, x_ℓ are distinct.
3. Equations $e_1 \dots, e_{k-2}$ are linearly independent.

We say that $z_1, \dots, z_k$ satisfy a (k,h)-gadget $\mathcal{E}$ if they satisfy the $k-2$ equations of $\mathcal{E}$. Note that any gadget $\mathcal{E}$ has a trivial solution $x_1 = \dots = x_k$.

Definition 2.2. **((k,h)-Gadget-Free)** A set of integers Z, is called (k,h)-*gadget-free* if there are no k **distinct** integers $z_1, \dots, z_k \in Z$ that satisfy an arbitrary (k,h)-gadget.

Our main goal in this section is to prove the following theorem, which will be a key ingredient in the lower-bounds for $\mathcal{P}^*_D$.

Theorem 2.3. *For every h and k there is an integer $c = c(k,h)$, such that for every n there is a $(k+1,h)$-gadget-free subset $Z \subset [n] = \{1, 2, \dots, n\}$ of size at least*

$$|Z| \ge \frac{n}{e^{c(\log n)^{1/\lfloor \log 2k \rfloor}}} \quad . \tag{2.1}$$

As we have explained before, note that for larger k the above theorem guarantees the existence of a substantially larger set Z. The special case of the above theorem, where $k = 2$, was proved and used in [9] and [4]. As the details of the proof of Theorem 2.3 will reveal, the main idea is to somehow reduce the construction required to prove Theorem 2.3 to a construction related to a notion very similar to arithmetic progressions. The main idea of this reduction will be to show that integers satisfying the linear equations of a gadget nearly form an arithmetic progression. Our notion of "near" arithmetic progression is the following:

Definition 2.4. **((k,h)-Progression)** A set of k integers $z_1 \le z_2 \le \ldots \le z_k$ is said to form a (k,h)-*progression* if there are integers $d, n_2, \ldots, n_k$ with $n_i \le h$ such that, for $2 \le i \le k$, we have

$$z_i = z_{i-1} + n_i d \quad . \tag{2.2}$$

In what follows we call the integers n_i the *coefficients* of the progression and d the *difference*. Note that a (k,h)-progression is "nearly" an arithmetic progressions in the sense that in an arithmetic progression one requires $n_2 = \ldots = n_k = 1$. Also, note that the difference d is analogous to the difference between consecutive elements in an arithmetic progression. In other words, a k-term arithmetic progression is a $(k,1)$-progression of distinct elements. The following notion will be important for the proof of Theorem 2.3:

Definition 2.5. **(Nontrivial (k,h)-Progression)** A (k,h)-progression is said to be *nontrivial* if its elements are distinct. Thus, a (k,h)-progression is nontrivial iff the difference d as well as the coefficients n_i are all nonzero.

The proof of Theorem 2.3 appears in the following two subsections. In the first subsection we show how to transform the problem from one that deals with linear equations and gadgets to an analogous problem about (k,h)-progressions. We also show how the solution of the problem about (k,h)-progressions implies Theorem 2.3. In the second subsection we solve the problem about (k,h)-progressions.

2.2 Gadgets and (k,h)-Progressions

We start this subsection by "reducing" gadgets to (k,h)-progressions. Formally, we want to show the following

Lemma 2.6. *For every k and h there is an integer $c = c(k,h)$ such that if $z_1 < \ldots < z_k$ satisfy a (k,h)-gadget then they form a nontrivial (k,c)-progression.*

For the proof of the above proposition we need the following three claims. For the proof of the first we need the following well-known result that follows from Cramer's rule and the Hadamard Inequality (see, e.g., [16]).

Lemma 2.7. *Let Ψ be a set of p homogenous linear equations in q variables. If $p < q$ and each of the coefficients in these equations has absolute value at most r, then Ψ has a* nonzero *solution $\{\alpha_1, \ldots, \alpha_q\}$, where each α_i is an* integer *with absolute value at most $(r^2 p)^{p/2}$.*

Claim 2.8. *If $z_1 < \ldots < z_k$ are positive integers, which satisfy a (k,h)-gadget $\mathcal{E}$, then for $2 \le i \le k-1$ there are positive integers $a_i, b_i \le (h^2k)^{k/2}$ such that $a_i z_{i-1} + b_i z_{i+1} = (a_i + b_i) z_i$.*

Proof. As there is nothing to prove for $k = 3$, we assume $k \ge 4$. In order to simplify the notation, we show that there are positive integers $a, b \le (h^2k)^{k/2}$ such that

$$az_1 + bz_3 = (a+b)z_2 \quad . \tag{2.3}$$

The other $k-3$ cases are identical. We first substitute $z_1, \ldots, z_k$ into the set $\mathcal{E}$, and obtain $k-2$ linear equations of the form $p_t z_i + q_t z_j = (p_t + q_t) z_k$. Henceforth, when we refer to equation $e_t \in \mathcal{E}$ we will refer to the equation after we have substituted the integers z_i into it. Our goal is simply to show that there are $\alpha_1, \ldots, \alpha_{k-2}$ not all equal to zero, such that in the linear combination $C = \alpha_1 e_1 + \ldots + \alpha_{k-2} e_{k-2}$ the coefficients of the integers $z_4, \ldots, z_k$ vanish. We first claim that this will give us (2.3). Indeed, note that as $e_1, \ldots, e_{k-2}$ are by assumption linearly independent, it cannot be the case that all the coefficients of the integers z_i vanish. Also, as for each of the equations in $\mathcal{E}$ the sum of the coefficients on the left hand side is equal to the coefficient on the right hand side, this must also hold for C, hence, it cannot be the case that precisely one of coefficients of z_1, z_2, z_3 does not vanish. Similarly, if precisely two of coefficients of z_1, z_2, z_3 do not vanish, this would imply that they are equal, which contradicts our assumption that $z_1 < \ldots < z_k$. Finally as we assume that each of the integers z_i appears at least once, we are guaranteed to get (2.3).

In order to make sure that in a linear combination with coefficients $\alpha_1, \ldots, \alpha_{k-2}$ the integers $z_4, \ldots, z_k$ vanish, we may write $k-3$ homogenous linear equations, which require that. This is a set of $k-3$ homogenous equations in $k-2$ unknowns with coefficients bounded by h. Therefore, by Lemma 2.7 it has a nonzero solution with integer coefficients of size at most $(h^2(k-2))^{k/2-1}$. This means that the coefficients of C are bounded by $(k-3)(h^2(k-2))^{k/2-1} \le (h^2k)^{k/2}$, as needed. □

Claim 2.9. *Suppose z_1, z_2, z_3, a, b are positive integers, such that $z_1 < z_2 < z_3$ and $a, b \le h$. If the following equation holds*

$$az_1 + bz_3 = (a+b)z_2 \quad ,$$

then z_1, z_2, z_3 form a nontrivial $(3,h)$-progression.

Proof. We show that z_1, z_2, z_3 form a $(3,h)$-progression. It will be a nontrivial $(3,h)$-progression because we assume that $z_1 < z_2 < z_3$. We first assume that a and b are co-prime, as otherwise we can divide them by their gcd, and obtain a new equation $a'z_1 + b'z_3 = (a'+b')z_2$, with $a' < a, b' < b$. Rearranging the equation we get that $a(z_2 - z_1) = b(z_3 - z_2)$. As a and b are co-prime $d = (z_3 - z_2)/a = (z_2 - z_1)/b$ is an integer. Thus, we can write $z_2 = z_1 + bd$ and $z_3 = z_2 + ad$, and take $n_2 = b \le h$ and $n_3 = a \le h$ in the definition of the $(3,h)$-progression. □

Claim 2.10. *Suppose $z_1 < z_2 < \ldots < z_k$ are positive integers, such that for every $2 \le i \le k-1$ there are integers $a_i, b_i \le h$, such that*

$$a_i z_{i-1} + b_i z_{i+1} = (a_i + b_i) z_i$$

holds. Then $z_1, z_2, \ldots, z_k$ form a (nontrivial) (k, h^{k-2})-progression.

Proof. As before, we show that $z_1,\dots,z_k$ form a (k,h^{k-2})-progression. It will be a nontrivial (k,h^{k-2})-progression because we assume that $z_1 < z_2 < \dots < z_k$. We proceed by induction on k. The base case $k=3$ follows from Claim 2.9. Assuming the claim holds for k we prove it for $k+1$. By the induction hypothesis, for $2 \le i \le k$ we can write $z_i = z_{i-1} + m_i t$ for some integer t and $m_i \le h^{k-2}$. By assumption $a_k z_{k-1} + b_k z_{k+1} = (a_k+b_k)z_k$. Rearranging this gives

$$z_{k+1} - z_k = \frac{a_k}{b_k}(z_k - z_{k-1}) \quad . \tag{2.4}$$

Put $g = \gcd(b_k,t)$ $(\le h)$ and $d = t/g$, and observe that for $1 \le i \le k$ we can write $z_i = z_{i-1} + g \cdot m_i \cdot d$, and thus take $n_i = m_i \cdot g \le hh^{k-2} = h^{k-1}$. As in Claim 2.9, we may assume that a_k and b_k are co-prime, and conclude from (2.4) that b_k divides $z_k - z_{k-1} = m_k t$. We may thus write

$$z_{k+1} = z_k + \frac{a_k m_k t}{b_k} = z_k + \frac{a_k m_k g}{b_k} \cdot d = z_k + n_{k+1} d \quad .$$

As $a_k g/b_k \le a_k \le h$ and $m_k \le h^{k-2}$, we have $n_{k+1} \le h^{k-1}$, and the proof is complete. □

Proof of Lemma 2.6. Immediate from Claim 2.8 and Claim 2.10. □

Though we do not need this here, it is worth mentioning that the converse of Lemma 2.6 is also true. Indeed, if $z_1,\dots,z_k$ form a (k,h)-progression, then for every $2 \le i \le k-1$ we have $z_i = z_{i-1} + n_i d$, and $z_{i+1} = z_i + n_{i+1} d$. This implies that $(n_i + n_{i+1}) z_i = n_{i+1} z_{i-1} + n_i z_{i+1}$. Hence, $z_1,\dots,z_k$ satisfy the $k-2$ linear equations $(n_i + n_{i+1}) x_i = n_{i+1} x_{i-1} + n_i x_{i+1}$ that are easily checked to satisfy the three requirements of a (k,h)-gadget.

The proof of Theorem 2.3 will follow by combining Lemma 2.6 and the following lemma.

Lemma 2.11. *For every h and $p \ge 2$, there is an integer $c = c(p,h)$ such that for every n there is a subset $Z \subset [n] = \{1,2,\dots,n\}$ of size at least*

$$|Z| \ge \frac{n}{e^{c \log^{1/p} n}} \tag{2.5}$$

that does not contain any nontrivial $(1+2^{p-1},h)$-progression.

Proof of Theorem 2.3. Let p be the largest integer satisfying $1+2^{p-1} \le 1+k$, namely, $p = \lfloor \log 2k \rfloor$. Let $c' = c(k+1,h)$ be the constant appearing in Lemma 2.6. Now, by Lemma 2.11, there is a constant $c = c(p,c')$, such that for every n there is a subset $Z \subseteq [n]$ of size as in (2.5), which contains no nontrivial $(1+2^{p-1},c')$-progression. By our choice of p, this set contains no nontrivial $(k+1,c')$-progression. By Lemma 2.6, the set Z does not contain $k+1$ distinct integers, which satisfy a $(k+1,h)$-gadget. As $p = \lfloor \log 2k \rfloor$, the set Z satisfies the requirements of Theorem 2.3. □

It is easy to see that the elements of a $(1+2^{p-1},h)$-progression must be taken from an arithmetic progression of length at most $h2^{p-1}$, whose difference is the integer d from the definition of the $(1+2^{p-1},h)$-progression in Definition 2.4. Thus, another way to look at Lemma 2.11 is as a construction of a set Z with the following property: not only doesn't Z contain arithmetic progressions of length $1+2^{p-1}$, but it does not even contain $1+2^{p-1}$ numbers out of some other not too large arithmetic progression, whose other elements need not even belong to Z.

In order to prove Lemma 2.11, we will first show that it holds for every *fixed* set of coefficients $n_2,\ldots,n_{1+2^{p-1}}$. Namely, we show that there is a subset of $[n]$ of the same size as in (2.5) that does not contain any $(1+2^{p-1},h)$-progression $z_1,\ldots,z_{1+2^{p-1}}$ such that $z_i = z_{i-1}+n_i d$ for every $2 \le i \le 1+2^{p-1}$. Note that the difference d may be arbitrary. To be precise, we want to show the following:

Lemma 2.12. *For every fixed positive $n_2,\ldots,n_{1+2^{p-1}} \le h$ there is an integer $c = c(p,h)$ such that for every n there is a subset $Z \subset [n] = \{1,2,\ldots,n\}$ of size at least*

$$|Z| \ge \frac{n}{e^{c\log^{1/p} n}} \quad , \tag{2.6}$$

that does not contain any nontrivial $(1+2^{p-1},h)$-progression with coefficients $n_2,\ldots,n_{2^p-1}$.

The proof of this lemma appears in the next subsection. We first show how to derive Lemma 2.11 from the above lemma.

Proof of Lemma 2.11. For every set s, of positive 2^{p-1} integers $n_2,\ldots,n_{1+2^{p-1}} \le h$, let Z_s be the largest subset of $[n]$, which does not contain any nontrivial $(1+2^{p-1},h)$-progression with coefficients $n_2,\ldots,n_{1+2^{p-1}}$. By Lemma 2.12 we have that for any s the set Z_s has size at least $n/e^{c\log^{1/p} n}$, where c depends only on p and h. Denote the number of sets s by m, and observe that as the coefficients in each set s are bounded by h there are less than 2^{ph} choices for the set s.

Uniformly at random pick m integers $t_1,\ldots,t_m$ from $\{-n,\ldots,n\}$, and consider the set

$$Z = \bigcap_{i=1}^{m}(Z_i + t_i)$$

(where, $Z+t$ denotes the translate of Z by t, i.e. $Z+t = \{z+t : z \in Z\}$). Clearly Z contains no $(1+2^{p-1},h)$-progressions with arbitrary coefficients bounded by h. For every integer $z \in [n]$ the probability that it belongs to Z_i+t_i is $1/e^{c\log^{1/p} n}$, hence the probability that it belongs to all the sets Z_i+t_i, and therefore also to Z, is $(1/e^{c\log^{1/p} n})^m = 1/e^{c'\log^{1/p} n}$ for a possibly larger c' that still depends only on p and h. By linearity of expectation we get that the expected size of Z is $n/e^{c'\log^{1/p} n}$, and therefore there is some choice of $t_1,\ldots,t_m$ for which the resulting set Z is at least this large. $\square$

2.3 Large sets of integers without a given (k,h)-Progression

In this subsection we apply the method of [18] in order to prove Lemma 2.12. The proof will require some more definitions. We first need to further extend the notion of arithmetic progressions as follows:

Definition 2.13 (**(p,t,h)-Progression**)**.** A set of p integers $z_0,\ldots,z_{p-1}$ is said to form a (p,t,h)-*progression* if there are $t+1$ integers $d_0,\ldots,d_t$ and integers $n_0 = 0, n_1,\ldots,n_{p-1} \le h$ such that for $0 \le i \le p-1$

$$z_i = d_0 + n_i \cdot d_1 + n_i^2 \cdot d_2 + \ldots + n_i^t \cdot d_t \quad . \tag{2.7}$$

To avoid confusion, note that by definition $d_0 = z_0$, thus, we did not really need d_0 and n_0, which is fixed to be zero, in the above definition. However, this way of defining the integers of the set will make subsequent notation more compact. Note that unlike the definition of (k,h)-progressions in Definition 2.4, here we define each element of the sequence with respect to the smallest number $z_0 = d_0$, rather than the preceding one as in Definition 2.4. Therefore, a (p,h)-progression as defined in Definition 2.4 is also a $(p,1,h(p-1))$-progression as defined in (2.7).

Definition 2.14 (Nontrivial (p,t,h)-progression). We call a (p,t,h)-progression *nontrivial* if at least one of $d_1,\dots,d_t$ is nonzero and $n_0,\dots,n_{p-1}$ are distinct.

Definition 2.15 ($R_s(p,t,n)$). For a set s of p distinct integers $n_0 = 0, n_1 \dots, n_{p-1} \le h$, define $R_s(p,t,n)$ to be the largest possible size of a subset of $[n]$ which does not contain any nontrivial (p,t,h)-progression whose coefficients are the integers of s.

The proof of Lemma 2.12 will follow by combining the following two claims.

Claim 2.16. *For every set s, of $2t+1$ distinct integers bounded by h, there is an integer $c = c(t,h)$, such that*

$$R_s(2t+1,t,n) \ge \frac{n}{e^{c\sqrt{\log n}}} \quad . \tag{2.8}$$

Claim 2.17. *For every set s, of p distinct integers bounded by h, there is an integer $c = c(p,h)$, such that if $n = g^b$ and $p \ge t+1$, then*

$$R_s(p,t,n) \ge \frac{n \cdot R_s(p,2t,g^2 b)}{c^b g^2 b} \quad . \tag{2.9}$$

Proof of Lemma 2.12. As we have noted above, a (p,h)-progression as defined in Definition 2.4 is also a $(p,1,h(p-1))$-progression as defined in (2.7). Hence, we can prove Lemma 2.12 by showing that for every set s, of distinct[2] coefficients $n_0 = 0, n_1, \dots, n_{2^{p-1}} \le h2^{p-1}$ we have

$$R_s(1+2^{p-1},1,n) \ge \frac{n}{e^{c\log^{1/p} n}} \quad . \tag{2.10}$$

Consider any set s, of distinct integers bounded by $h2^{p-1}$. Given integers n and p, we prove by induction on ℓ that for every $2 \le \ell \le p$ there is a constant $c = c(p,h)$, such that

$$R_s(1+2^{p-1},2^{p-\ell},n) \ge \frac{n}{e^{c(\log n)^{1/\ell}}} \quad . \tag{2.11}$$

The case $\ell = 2$ follows from Claim 2.16 with $t = 2^{p-2}$. Assuming the claim holds for ℓ we prove it for $\ell+1$. Set $b = (\log n)^{1/(\ell+1)}$, and let g satisfy $n = g^b$, namely $g = e^{(\log n)^{1-1/(\ell+1)}}$. A short calculation shows that in this case

$$(\log g^2 b)^{1/\ell} \le c(\log n)^{1/(\ell+1)} \quad , \tag{2.12}$$

[2]The reader should recall that for a (p,t,h)-progressions to be nontrivial its coefficients should be distinct. When $t=1$ this guarantees that this nontrivial $(p,1,h)$-progression is also a nontrivial (p,h)-progression.

where c depends only on p. We get that

$$R(1+2^{p-1},2^{p-\ell-1},n) \geq \frac{n\cdot R(1+2^{p-1},2^{p-\ell},g^2b)}{c^b g^2 b}$$
$$\geq \frac{n}{c^b g^2 b}\cdot\frac{g^2 b}{e^{c(\log g^2 b)^{1/\ell}}} \geq \frac{n}{c^b e^{c(\log n)^{1/(\ell+1)}}} \geq \frac{n}{e^{c(\log n)^{1/(\ell+1)}}} \quad ,$$

where the first inequality follows from Claim 2.17, the second from the induction hypothesis in (2.11) with $n = g^2 b$, the third from (2.12), and the last from our choice of b and the fact that c depends only on p and h. Also, note that by the reasoning we used to derive each of these inequalities, all the above constants depend only on p and h (we called all of them c in order to simplify the notation). This completes the proof of (2.11). We now obtain (2.10) by setting $\ell = p$ in (2.11). □

We now turn to prove Claim 2.16 and Claim 2.17, which will require (yet again) several additional definitions. Given a set of integers S we denote by $S+r$ the *translate* of S by r, that is, $S+r = \{x+r : x \in S\}$. Note, that if S does not contain any nontrivial (p,t,h)-progression than so does any translate of S. For reasons that will soon become clear, we prefer to prove Claim 2.16 and Claim 2.17 with respect to the set of integers $\{-n/2,\dots,n/2\}$ rather than $[n] = \{1,\dots,n\}$. We also consider representations of integers from $\{-n/2,\dots,n/2\}$ in base g, where g will depend on n and will be much smaller than n. If $n = g^b$ we define, for an integer $c \geq 2$,

$$Q_c = \{x \in Z : x = \sum_{i=0}^{b-1} x_i \cdot g^i, -g/c \leq x_i \leq g/c\} \quad ,$$

namely, all the integers whose "digits" in base g belong to $-g/c,\dots,g/c$. As $Q_c \subseteq \{-n/2,\dots,n/2\}$ we may and will construct our sought after sets from integers belonging to Q_c for an appropriate large enough constant c. Note, that somewhat unconventionally, we allow for negative digits. This representation, however, is well-defined in the sense that given $x \in Q_c$, there are unique integers $-g/c \leq x_0,\dots,x_{b-1} \leq g/c$ such that $x = \sum_{i=0}^{b-1} x_i \cdot g^i$. Given an integer $x \in Q_c$ we will denote by $\overline{x} = (x_0,\dots,x_{b-1})$ the unique b dimensional vector in Z^b such that $x = \sum_{i=0}^{b-1} x_i \cdot g^i$. We will also denote $\|x\|^2 = \|\overline{x}\|^2 = \sum_{i=0}^{b-1} x_i^2$. Our argument will critically rely on the observation that if c is sufficiently large then addition, and more generally linear combinations with small coefficients, of numbers from Q_c is equivalent to linear combinations of their corresponding vectors. For example, observe that if $x,y,z \in Q_2$, then $x+y = z$ if and only if $\overline{x}+\overline{y} = \overline{z}$. The reason for that is simply that there is no carry in the base g addition of the number. More generally, if c is sufficiently large with respect to integers $\alpha_1,\dots,\alpha_t$, then for $x,x_1,\dots,x_t \in Q_c$,

$$x = \sum_{i=1}^{t} \alpha_i \cdot x_i \Longleftrightarrow \overline{x} = \sum_{i=1}^{t} \alpha_i \cdot \overline{x_i} \quad . \tag{2.13}$$

Also, note that if c is sufficiently large with respect to integers $\alpha_1,\dots,\alpha_t$, then for $x_1,\dots,x_t \in Q_c$,

$$\overline{x} = \sum_{i=1}^{t} \alpha_i \cdot \overline{x_i} \in Q_{c'} \quad , \tag{2.14}$$

for another (possibly smaller) constant c'. It should be noted that had we chosen to work with the set $[n]$ rather than $-n/2,\ldots,n/2$ and represented integers using positive digits, then (2.13) and (2.14) would not necessarily hold for negative coefficients. The reason is that the difference of two numbers with small digits may contain very large digits. As we also allow for negative digits, the difference also contains small digits. Finally, given integers $p_1,\ldots,p_t$ we denote by $V(p_1,\ldots,p_t)$ the Vandermonde matrix satisfying for $1 \le i,j \le t$, $V_{i,j} = p_i^j$.

Proof of Claim 2.16. Consider any set s of $2t+1$ distinct integers $n_0 = 0, n_1, \ldots, n_{2t} \le h$. For an integer r define $S_r = \{x \in Q_c : \|x\|^2 = r\}$. We claim that if c is large enough in terms of t and h, then S_r contains no nontrivial $(2t+1,t,h)$-progression with coefficients taken from s. Suppose to the contrary that there are such $2t+1$ integers $z_0, z_1, \ldots, z_{2t}$. By (2.7) we have that for $0 \le i \le 2t$

$$z_i = d_0 + n_i \cdot d_1 + n_i^2 \cdot d_2 + \ldots + n_i^t \cdot d_t \quad , \tag{2.15}$$

where $d_0 = z_0, d_1, \ldots, d_t$ are arbitrary integers. Recall, that for this set to be nontrivial at least one of $d_1,\ldots,d_t$ must be nonzero (the integers $n_i \in s$ are already assumed to be distinct). Denote by D the determinant of the Vandermonde matrix $V = V(n_0,\ldots,n_t)$, and for $0 \le i \le t$ denote by D_i the determinant of the matrix obtained from V by replacing the i^{th} column with the column vector $(z_0,\ldots,z_t)$. Observe, that we can view the first $t+1$ equations in (2.15) as $t+1$ equations in unknowns $d_0,d_1,\ldots,d_t$. It follows from Cramer's rule that for $0 \le i \le t$ we have $Dd_i = D_i$. From the definition of the determinant we can view D_i as a linear combination of $z_0,\ldots,z_t$ with integer coefficients bounded by a constant that depends only on t and $n_0,n_1,\ldots,n_t$. As $n_0,n_1,\ldots,n_t \le h$, these coefficients are bounded by a constant that depends only on t and h. Hence, by (2.13), if c was chosen large enough in terms of t and h then for $0 \le i \le t$, we get that $\overline{Dd_i}$ (the b dimensional vector representing Dd_i) is a linear combination of $\overline{z_0},\ldots,\overline{z_t}$. Moreover, by (2.14) we may conclude that $\overline{Dd_i} \in Q_{c'}$ for some $c' < c$. As by (2.15), $z_0,\ldots,z_{2t}$ are defined as linear combinations of $d_0,\ldots,d_t$, we conclude that if c is large enough (so that c' is large enough), we can use (2.13) again to write (2.15) as

$$D\overline{z_i} = \overline{Dd_0} + n_i \cdot \overline{Dd_1} + n_i^2 \cdot \overline{Dd_2} + \ldots + n_i^t \cdot \overline{Dd_t} \quad . \tag{2.16}$$

Define the following polynomial of degree $2t$

$$P(x) := \sum_{q=0}^{b-1} \left((\overline{Dd_0})_q + (\overline{Dd_1})_q \cdot x + (\overline{Dd_2})_q \cdot x^2 + \ldots + (\overline{Dd_t})_q \cdot x^t \right)^2 \quad ,$$

where $(\overline{Dd_i})_q$ denotes the q^{th} entry of the vector $\overline{Dd_i}$. The key observation now is that by (2.16) we have for $0 \le j \le 2t$ that $P(n_j) = \|D\overline{z_j}\|^2 = D^2\|z_j\|^2$. Hence, as by assumption all the integers z_i belong to S_r, we have that P is a polynomial of degree $2t$ with $2t+1$ distinct values (namely $n_0,n_1,\ldots,n_{2t}$) for which it is equal to D^2r. Therefore, P must be identical to D^2r, which can be easily seen to imply that $(\overline{Dd_i})_q = 0$ for all $0 \le q \le d-1$ and $1 \le i \le t$. Hence, $d_1 = \ldots = d_t = 0$, contradicting our assumption that this is a nontrivial $(2t+1,t,h)$-progression. We conclude that if c is large enough in terms of h and t then S_r contains no nontrivial $(2t+1,t,h)$-progression.

The claim now follows by averaging. As the absolute value of each digit in Q_c is bounded by g/c, we have $r \le b(g/c)^2 \le bg^2$. Similarly, we conclude that Q_c is of size $(2g/c)^b > (g/c)^b$. As the union of the sets S_r covers the entire set Q_c there must be one r for which $|S_r| \geq (g/c)^b/bg^2 = n/bg^2c^b$. Setting $b = \sqrt{\log n}$, and hence $g = e^{\sqrt{\log n}}$, gives (2.8) for an appropriate constant $c = c(t,h)$. □

Proof of Claim 2.17. We again consider an arbitrary set s, of distinct integers $n_0 = 0, n_1, \ldots, n_{p-1}$ bounded by h. As in the previous proof, we continue to write $n = g^b$ and represent numbers in base g with possibly negative digits. We will also construct our sought after set from Q_c for a large enough constant c that will only depend on p,t and h. Let D denote the determinant of the Vandermonde matrix $V = V(n_0, \ldots, n_t)$. Let $R \subseteq \{1, \ldots, D^2b(g/c)^2\}$ be a set of size $R_s(p,2t,D^2b(g/c)^2)$ that contains no nontrivial $(p,2t,h)$-progression with coefficients from s, and recall that any translate of R also satisfies this property. Let $L = \{-D^2b(g/c)^2, \ldots, D^2b(g/c)^2\}$. For any $\ell \in L$ define

$$A_\ell = \{x \in Q_c : \|Dx\|^2 \in R + \ell\} \ .$$

We claim that A_ℓ does not contain any nontrivial (p,t,h)-progression, with coefficients from s, provided c in the definition of Q_c is large enough. Suppose this is not the case, and let $z_0, \ldots, z_{p-1}$ be such a nontrivial (p,t,h)-progression. Namely, suppose there are $d_0, d_1, \ldots, d_t$ not all equal to zero such that $z_j = d_0 + \sum_{i=1}^{t} n_j^t d_t$ holds for $0 \leq i \leq p-1$. As by assumption $p \geq t+1$ we can still write the $t+1$ linear equations as in (2.15). We can then argue as in the proof of Claim 2.16 that provided c is large enough, we may conclude that for $0 \leq j \leq p-1$ one can write

$$D\overline{z_i} = \overline{Dd_0} + n_i \cdot \overline{Dd_1} + n_i^2 \cdot \overline{Dd_2} + \ldots + n_i^t \cdot \overline{Dd_t} \ . \tag{2.17}$$

This implies, as in Claim 2.16, that for every $0 \leq j \leq p-1$ we can write

$$\|Dz_j\| = \|D\overline{z_j}\|^2 = \sum_{q=0}^{b-1} \left(\sum_{i=0}^{t} (\overline{Dd_i})_q \cdot n_j^i \right)^2 = d'_0 + n_j \cdot d'_1 + n_j^2 \cdot d'_2 + \ldots + n_j^{2t} \cdot d'_{2t} \ , \tag{2.18}$$

where $d'_0, \ldots, d'_{2t}$ are *identical* to all $0 \leq j \leq p-1$. It is easy to see that as $d_0, \ldots, d_t$ are by assumption not all zero, then so are $d'_0, \ldots, d'_{2t}$. As $d'_0, \ldots, d'_{2t}$ are common to all $\|Dz_j\|^2$, the right hand side of (2.18) has the structure of a nontrivial $(p,2t,h)$-progression with coefficients from s. This means that $\|Dz_0\|^2, \ldots, \|Dz_{t-1}\|^2$ form a nontrivial $(p,2t,h)$-progression with coefficients from s. This contradicts our choice of R and A_ℓ.

We conclude that for any $\ell \in L$, the set A_ℓ contains no nontrivial (p,t,h)-progression with coefficients from s. It is thus enough to show that for some $\ell \in L$ the set A_ℓ is large enough. We do this again by averaging. As the absolute value of the digits of numbers from Q_c is bounded by g/c we have $0 \leq \|Dx\|^2 \leq D^2b(g/c)^2$ for any $x \in Q_c$. Therefore, for any $r \in R$ and $x \in Q_c$ there is an $\ell \in L$ such that $\|Dx\|^2 = r + \ell$. Hence, for any $x \in Q_c$ there are $|R|$ integers $\ell \in L$ such that $x \in A_\ell$. In other words, $\sum_{\ell=1}^{|L|} A_\ell \geq |R||Q|$, and therefore for some choice of $\ell \in L$ we have $|A_\ell| \geq |R||Q_c|/|L|$. As $|Q_c| > (2g/c)^b$, the proof follows as for some $\ell \in L$ we must have

$$|A_b| \geq \frac{R(p,2t,h,D^2bg^2) \cdot (2g/c)^b}{D^2b(g/c)^2} \geq \frac{R(p,2t,h,bg^2) \cdot g^b}{D^2c^bbg^2} \geq n\frac{R(p,2t,h,bg^2)}{c^bbg^2} \ , \tag{2.19}$$

where we used the fact that by definition $n = g^b$ and D is bounded by a function of t and h only, therefore, we can use a slightly larger constant c to "absorb" D^2. □

3 Linear Equations and Extremal Hypergraphs

3.1 The main results of this section

In this section we describe the first algebraic construction of extremal k-graphs, which will play an important role in the proofs of Theorem 1.2 and Theorem 1.3 about testing $\mathcal{P}_D^*$ in Section 5. The second construction, related to $\mathcal{P}_D$ and Theorem 1.7, appears in Section 6. The following definition will be key for what follows:

Definition 3.1 ($\mathcal{T}^k$)**.** Let $\mathcal{T}^k$ denote the family of k-graphs on $k+1$ vertices, which contain **at least** three edges.

Let m be an integer, T a member of $\mathcal{T}^k$, and Z an arbitrary subset of $[m]$. Let also $P_d = \{p_1, \dots, p_{k+1}\}$ be a set of $k+1$ *distinct* integers bounded by d (thus $d > k$). Consider the following definition of a k-graph $S = S(m, Z, T, P_d)$: The vertex set of S consists of $k+1$ pairwise disjoint sets of vertices $V_1, \dots, V_{k+1}$, where, with a slight abuse of notation, we think of each of these sets as being the set of integers $1, \dots, d^k m$. Define

$$E(z_0, z_1, \dots, z_{k-1}, p) = z_0 + p \cdot z_1 + p^2 \cdot z_2 + p^3 \cdot z_3 + \dots + p^{k-1} \cdot z_{k-1} \quad . \tag{3.1}$$

We define the edge set of S by specifying the edge sets of $|Z|^k$ copies of T that we put in S. In what follows we refer to the $k+1$ vertices of T as integers in $\{1, \dots, k+1\}$. For every set of (not necessarily distinct) integers $z_0, \dots, z_{k-1} \in Z$, we add to S a copy of T that is spanned by the vertices $v_1 \in V_1, \dots, v_{k+1} \in V_{k+1}$, where for $1 \le i \le k+1$ we choose $v_i = E(z_0, \dots, z_{k-1}, p_i)$. In order to specify the edges of this copy, we simply regard the vertices $v_1, \dots, v_{k+1}$ as if they were the vertices $1, \dots, k+1$ of a regular copy of T and put in the corresponding edges. Namely, for every edge $(t_1, \dots, t_k) \in E(T)$, we add to S an edge that contains the vertices

$$E(z_0, \dots, z_{k-1}, p_{t_1}) \in V_{t_1}, \;\; E(z_0, \dots, z_{k-1}, p_{t_2}) \in V_{t_2}, \;\; \dots \;\; , E(z_0, \dots, z_{k-1}, p_{t_k}) \in V_{t_k} \quad .$$

In what follows we denote by $C(z_0, \dots, z_{k-1})$, the copy of T defined using the integers $z_0, \dots, z_{k-1}$. Note, that each of these $|Z|^k$ copies of D has precisely one vertex in each of the sets $V_1, \dots, V_{k+1}$. Note also, that for every $z_0, \dots, z_{k-1}$ and p_i, the function E satisfies

$$1 \le E(z_0, \dots, z_{k-1}, p_i) \le k d^{k-1} m \le d^k m \quad ,$$

thus the vertices "fit" into the sets $V_1, \dots, V_{k+1}$. The reader should also observe that we treat the set of integers P_d, as an *ordered* set, as when choosing the vertex from V_i we use the integer $p_i \in P_d$. Our first goal in this section is to prove the following lemma.

Lemma 3.2. (The Key Lemma) *Let T be a member of $\mathcal{T}^k$, m an arbitrary integer, Z a subset of $[m]$ and P_d a set of $k+1$ distinct integers bounded by d. Define $S = S(m, Z, T, P_d)$, and suppose E_1, E_2, E_3 are three edges that belong to a copy of T in S. If $E_1 \in C(a_0, \dots, a_{k-1})$, $E_2 \in C(b_0, \dots, b_{k-1})$ and $E_3 \in C(c_0, \dots, c_{k-1})$, and if $a_i \le c_i \le b_i$ for some i, $0 \le i \le k-1$, then either $a_i = b_i = c_i$ or there are positive integers $\beta_1, \beta_2 \le d^{3d^2}$ such that*

$$\beta_1 a_i + \beta_2 b_i = (\beta_1 + \beta_2) c_i \quad .$$

Using the above lemma, we will construct the following extremal k-graph, which will be a key ingredient in the lower bounds of Theorem 1.2 and Theorem 1.3.

Lemma 3.3. *For every fixed k-graph D on d vertices that contains a copy of $T \in \mathfrak{T}^k$ with $r \geq 3$ edges, an integer m and a (r, d^{3d^2})-gadget-free set $Z \subset [m/d^{k+2}]$, there is a k-graph F on m vertices with the following properties:*

1. *F contains $|Z|^k$ induced copies of D, which are singled out from the rest of the copies of D and are called the* essential copies *of D in F.*
2. *Each pair of these essential copies share at most $k-1$ common vertices.*
3. *Every copy of T belongs to one of the essential copies of D.*

It is important to note that we do not claim that F does not contain any copies of D other than the $|Z|^k$ essential copies, nor will we claim so later on in this section. As the statement of the above lemma is rather technical, the reader can find in Section 3.3 a short intuitive explanation of it.

3.2 Proof of Lemma 3.2

The main idea of the proof is very simple; as T has only $k+1$ vertices, the 3 edges spanned by these vertices must have many common vertices. As the vertices of each set were chosen using the function E defined in (3.1), we get from each vertex that is common to, say, E_1 and E_2, a linear equation that relates the integers $a_0, \ldots, a_{k-1}$, which were used to define E_1 and the integers $b_0, \ldots, b_{k-1}$, which were used to define E_2. We then show that for every i either $a_i = b_i = c_i$ or the linear equations induced by the intersections of the edges are "reach" enough to enable us to extract a linear equation of the form $\beta_1 a_i + \beta_2 b_i = (\beta_1 + \beta_2) c_i$.

Let E_1, E_2 and E_3 be three edges that belong to a copy of a member of $T \in \mathfrak{T}^k$. As T has $k+1$ vertices and any k-graph on $k+1$ vertices that contains at least 3 edges is a core (recall Definition 1.5), the $k+1$ vertices must belong to distinct sets V_i. Call these vertices $v_1 \in V_1, \ldots, v_{k+1} \in V_{k+1}$. Assume, without loss of generality, that $E_1 = \{v_1, \ldots, v_{k+1}\} \setminus v_{k+1}$, $E_2 = \{v_1, \ldots, v_{k+1}\} \setminus v_k$ and $E_3 = \{v_1, \ldots, v_{k+1}\} \setminus v_{k-1}$. Recall, that every edge in S belongs to one of the copies of T, defined using some k integers from Z. Suppose $E_1 \in C(a_0, \ldots, a_{k-1})$, $E_2 \in C(b_0, \ldots, b_{k-1})$, and $E_3 \in C(c_0, \ldots, c_{k-1})$. As $v_1 \in V_1, \ldots, v_{k-1} \in V_{k-1}$, are common to both E_1 and E_2 we conclude that for every $i \in [k+1] \setminus \{k, k+1\}$, the following equation holds:

$$E(a_0, \ldots, a_{k-1}, p_i) = v_i = E(b_0, \ldots, b_{k-1}, p_i) \ .$$

As $v_1 \in V_1, \ldots, v_{k-2} \in V_{k-2}, v_k \in V_k$, are common to both E_1 and E_3 we conclude that for every $i \in [k+1] \setminus \{k-1, k+1\}$, the following equation holds:

$$E(a_0, \ldots, a_{k-1}, p_i) = v_i = E(c_0, \ldots, c_{k-1}, p_i) \ .$$

We could have written $k-1$ equations for the common vertices of E_2 and E_3, however, all but one of them follow from the previous equations. The only independent equation is due to v_{k+1}:

$$E(b_0, \ldots, b_{k-1}, p_{k+1}) = v_{k+1} = E(c_0, \ldots, c_{k-1}, p_{k+1}) \ .$$

We get a set of $2k-1$ equations in $3k$ unknowns, $a_0,\ldots,a_{k-1}$, $b_0,\ldots,b_{k-1}$ and $c_0,\ldots,c_{k-1}$. In order to simplify the rest of this subsection, we substitute the definition of E from (3.1) and write our set of equations as follows:

$$
\begin{aligned}
a_0+p_1a_1+p_1^2a_2+\ldots+p_1^{k-1}a_{k-1} &= b_0+p_1b_1+p_1^2b_2+\ldots+p_1^{k-1}b_{k-1}\\
a_0+p_2a_1+p_2^2a_2+\ldots+p_2^{k-1}a_{k-1} &= b_0+p_2b_1+p_2^2b_2+\ldots+p_2^{k-1}b_{k-1}\\
&\vdots\\
a_0+p_{k-1}a_1+p_{k-1}^2a_2+\ldots+p_{k-1}^{k-1}a_{k-1} &= b_0+p_{k-1}b_1+p_{k-1}^2b_2+\ldots+p_{k-1}^{k-1}b_{k-1}\\
a_0+p_1a_1+p_1^2a_2+\ldots+p_1^{k-1}a_{k-1} &= c_0+p_1c_1+p_1^2c_2+\ldots+p_1^{k-1}c_{k-1}\\
a_0+p_2a_1+p_2^2a_2+\ldots+p_2^{k-1}a_{k-1} &= c_0+p_2c_1+p_2^2c_2+\ldots+p_2^{k-1}c_{k-1}\\
&\vdots\\
a_0+p_{k-2}a_1+p_{k-2}^2a_2+\ldots+p_{k-2}^{k-1}a_{k-1} &= c_0+p_{k-2}c_1+p_{k-2}^2c_2+\ldots+p_{k-2}^{k-1}c_{k-1}\\
a_0+p_ka_1+p_k^2a_2+\ldots+p_k^{k-1}a_{k-1} &= c_0+p_kc_1+p_k^2c_2+\ldots+p_k^{k-1}c_{k-1}\\
b_0+p_{k+1}b_1+p_{k+1}^2b_2+\ldots+p_{k+1}^{k-1}b_{k-1} &= c_0+p_{k+1}c_1+p_{k+1}^2c_2+\ldots+p_{k+1}^{k-1}c_{k-1}
\end{aligned}
$$

In what follows we denote by Φ the above set of equations. The main idea of the proof will be to show that either $a_0=b_0=c_0$ or there is a linear combination of Φ with *integer coefficients* $\alpha_1,\ldots,\alpha_{2k-1}$, which results in the required linear equation relating a_0,b_0 and c_0. The other cases relating a_i,b_i,c_i with $i>0$ are completely identical. The main idea is to find a linear combination in which for $1\le i\le k-1$ the coefficients of a_i,b_i and c_i vanish. To this end, we introduce a set of equations whose solution will be our desired integers α_i. Observing Φ, we see that each a_i appears on the left hand side of the first $2k-2$ equations. Thus, in order for the coefficient of a_i to vanish in a linear combination of Φ with coefficients $\alpha_1,\ldots,\alpha_{2k-1}$, the following equation must hold

$$A_i: \qquad \alpha_1\cdot p_1^i+\alpha_2\cdot p_2^i+\ldots+\alpha_{2k-3}\cdot p_{k-2}^i+\alpha_{2k-2}\cdot p_k^i=0 \ .$$

Each b_i appears only on the right hand side of the first $k-1$ equations and on the left hand side of the last equation. Therefore, in order for the coefficient of b_i to vanish the following equation must hold

$$B_i: \qquad {}_1\cdot p_1^i+\alpha_2\cdot p_2^i+\ldots+\alpha_{k-1}\cdot p_{k-1}^i-\alpha_{2k-1}\cdot p_{k+1}^i=0 \ .$$

Finally, each c_i appears only on the right hand side of the last $k-1$ equations. Hence, in order for the coefficient of c_i to vanish the following equation must hold

$$C_i: \qquad {}_k\cdot p_1^i+\alpha_{k+1}\cdot p_2^i+\ldots+\alpha_{2k-3}\cdot p_{k-2}^i+\alpha_{2k-2}\cdot p_k^i+\alpha_{2k-1}\cdot p_{k+1}^i=0 \ .$$

Observe, that we can write the analogous linear equations A_0,B_0 and C_0 that will require the coefficients of a_0,b_0 and c_0 to vanish. Though we apparently don't need these equations, they will be useful for the proof. In what follows we denote by Υ the set of equations $A_1,\ldots,A_{k-1}$, $B_1,\ldots,B_{k-1}$, and $C_1,\dots,C_{k-1}$. The set Υ consists of $3k-3$ homogenous linear equations in $2k-1$ unknowns $\alpha_1,\dots,\alpha_{2k-1}$. Observe, however, that for $1 \le i \le k-1$,

$$A_i = B_i + C_i \ .$$

Therefore, Υ is equivalent to a set of $3k-3-(k-1) = 2k-2$ linear homogenous equations in $2k-1$ unknowns, which consists of equations B_i, C_i . Observe also, that each of the coefficients in Υ has absolute value at most d^k (recall that $1 \le p_1,\dots,p_{k+1} \le d$). By Lemma 2.7, we are thus guaranteed that there are *integers* $\alpha_1,\dots,\alpha_{2k-1}$ not all equal to zero, whose absolute values are at most $(d^{2k}(2k-2))^{k-1} \le d^{2d^2}$, such that in a linear combination of the above equations the coefficients of all the variables but a_0,b_0,c_0 vanish. We now claim that in such a combination either the coefficient of b_0 or the coefficient of c_0 does not vanish. An important observation is that as the integers $p_1,\dots,p_{k+1}$ are distinct, the k linear equations $B_0,\dots,B_{k-1}$ that require the coefficients of $b_0,\dots,b_{k-1}$ to vanish are linearly independent. Hence, their only solution is $\alpha_1 = 0,\dots,\alpha_{k-1} = 0, \alpha_{2k-1} = 0$. Similarly, the k linear equations $C_0,\dots,C_{k-1}$ that require the coefficients of $c_0,\dots,c_{k_1}$ to vanish are linearly independent. Hence, their only solution is $\alpha_k = 0,\dots,\alpha_{2k-1} = 0$. Thus, if the coefficients of b_0 and c_0 vanish we may conclude that we must have used a linear combination with $\alpha_1 = \ldots = \alpha_{2k-1} = 0$, which contradicts our choice.

Note, that as in each of the equations of Φ the sum of the coefficients on the right hand side is equal to the sum of the coefficients on the left hand side, this property must also hold in a linear combination of Φ. Hence, there is no linear combination in which the coefficient of precisely one of a_0,b_0,c_0 does not vanish. It also follows that if the coefficients of precisely two of a_0,b_0,c_0 do not vanish, then they must be equal. However, if for example $a_0 = b_0$, then we can "replace" b_0 with a_0 in the last equation of Φ, and use the last k equations of Φ to infer that for $1 \le i \le k-1$ we have $a_i = c_i$. We would thus get that $a_0 = b_0 = c_0$, which satisfies the requirement of the lemma. The other two cases are similar. As in the previous paragraph we have ruled out the possibility that the coefficients of a_0,b_0 and c_0 vanish, the remaining possibility is that the coefficients a_0,b_0 and c_0 do not vanish. In this case, we can use again the fact that in the resultant equation the sums of the coefficients in each side are equal to infer that we must get the required equation. Finally, as the coefficients α_i are bounded by d^{2d^2}, the coefficients in the linear combination are bounded by $(2k-1)d^{2d^2} < d^{3d^2}$.

3.3 Intuition for Lemma 3.3

We give some explanation as to why, or more precisely *when*, Lemma 3.3 is not trivial. Consider for simplicity the case of $k = 2$, that is, when $\mathcal{T}^k$ is simply a triangle, and D is a K_4 (a clique of size 4). In this case, the lemma says that we can construct a graph on m vertices that contains $|Z|^2$ essential copies of K_4 that are pairwise edge disjoint, and such that each triangle in the graph belongs to one of these copies of K_4. Note, that if $|Z| = 1$ this statement is trivial as we can simply take a single copy of K_4 in order to construct such a graph. However, if $|Z| = m^{1-o(1)}$, the lemma claims that we can construct the following nontrivial graph: It has m vertices and $|Z|^2 = m^{2-o(1)}$ essential copies of K_4 that are pairwise edge disjoint, such that each triangle in the graph belongs to one of these copies of K_4. As each K_4 contains at most 4 triangles, this graph contains less than m^2 triangles. As any triangle appears in at most m copies of K_4 such a graph has at most m^3 copies of K_4. Note that any trivial such construction (e.g. random) will contain roughly $m^{4-o(1)}$ copies of K_4. The fact that we can construct graphs that contain many induced copies of a graph, where each two copies have at most 1 common vertex (or $k-1$ vertices in the case of k-graphs) while containing relatively few copies of it, will be crucial in the proofs of Theorem 1.2 and Theorem 1.3.

3.4 Proof of Lemma 3.3

We define a k-graph F, similar to the one used in Lemma 3.2. The vertex set of F consists of d pairwise disjoint sets of vertices $V_1,\ldots,V_d$, where, with a slight abuse of notation, we think of each of these sets as being the set of integers $1,\ldots,m/d$. We define the edge set of F by specifying the edge sets of $|Z|^k$ copies of D that we put in F. In what follows we refer to the d vertices of D as integers in $\{1,\ldots,d\}$.

For every set of (not necessarily distinct) integers $z_0,\ldots,z_{k-1} \in Z$, we add to F a copy of D that is spanned by the vertices $v_1 \in V_1,\ldots,v_d \in V_d$, where for $1 \le i \le d$ we choose $v_i = E(z_0,\ldots,z_{k-1},i)$. In order to specify the edges of this copy, we simply regard the vertices $v_1,\ldots,v_d$ as if they were the vertices of a regular copy of D and put in the corresponding edges. Namely, for every edge $(p_1,\ldots,p_k) \in E(T)$, we put in F an edge that contains the vertices

$$E(z_0,\ldots,z_{k-1},p_1) \in V_{p_1},\ \ E(z_0,\ldots,z_{k-1},p_2) \in V_{p_2},\ \ldots\ ,E(z_0,\ldots,z_{k-1},p_k) \in V_{p_k}\ \ .$$

In what follows we denote by $C(z_0,\ldots,z_{k-1})$, the copy of D defined using the integers $z_0,\ldots,z_{k-1}$. This defines $|Z|^k$ copies of D. These $|Z|^k$ copies of D will be the essential copies of D in F in the statement of the lemma (but we will still have to show that they are induced copies of D in F). Observe, that any essential copy D has precisely one vertex in each of the sets $V_1,\ldots,V_d$. Note also, that as $Z \subseteq [m/d^{k+2}]$, for every $z_0,\ldots,z_{k-1}$ and $1 \le i \le d$, the function E satisfies $1 \le E(z_0,\ldots,z_{k-1},i) \le kd^{k-1}m/d^{k+2} \le m/d$, thus the vertices "fit" into the sets $V_1,\ldots,V_d$.

We now turn to prove the assertions of the lemma. Let $v_1,\ldots,v_k$ be k vertices that belong to one of the essential copies of D in F. As the vertices of an essential copy belong to different sets V_i, there are *distinct* integers $1 \le p_1,\ldots,p_k \le d$, such that $v_1 \in V_{p_1},\ldots,v_k \in V_{p_k}$. From the definitions of F and the function E in (3.1), there are $z_0,\ldots,z_{k-1}$, such that the following equations hold:

$$z_0 + p_1 z_1 + p_1^2 z_2 + \ldots + p_1^{k-1} z_{k-1} = E(z_0,\ldots,z_{k-1},p_1) = v_1\ \ ,$$
$$\vdots$$
$$z_0 + p_k z_1 + p_k^2 z_2 + \ldots + p_k^{k-1} z_{k-1} = E(z_0,\ldots,z_{k-1},p_k) = v_k\ \ .$$

If we view the following equations as a set of k linear equations with unknowns $z_0,\ldots,z_{k-1}$, they correspond to the matrix equation $Ax = b$, where $b = \{v_1,\ldots,v_k\}$, $x = \{z_0,\ldots,z_{k-1}\}$, and $A_{i,j} = p_i^{j-1}$. As A is an invertible Vandermonde matrix (here we use the fact that the integers p_i are distinct), we conclude that $z_0,\ldots,z_{k-1}$ are uniquely defined by this set of equations. Hence, they belong to precisely one of the essential copies of D, namely, $C(z_0,\ldots,z_{k-1})$. We have thus shown that each pair of essential copies share at most $k-1$ common vertices. As F is a k-graph, the essential copies of D are in particular edge disjoint. As by definition, every edge in D belongs to one of the essential copies of D, we conclude that the essential copies of D in F are in fact *induced*. We have thus proved items (1) and (2).

We now turn to prove item (3). Suppose $v_1,\ldots,v_{k+1}$ are $k+1$ vertices that span a copy of T, namely, they span $r \ge 3$ edges. As any member of $\mathcal{T}^k$ contains at least 3 edges, T is a core (recall Definition 1.5).

Hence, there are distinct $p_1,\ldots,p_{k+1}$ such that $v_1 \in V_{p_1},\ldots,v_{k+1} \in V_{p_{k+1}}$. Suppose the r edges of T are $e_1 \in C(z_{0,1},\ldots,z_{k-1,1}),\ldots,e_r \in C(z_{0,r},\ldots,z_{k-1,r})$. In order to show that each copy of T belongs to one of the essential copies of D we may show that for $0 \le i \le k-1$ we have $z_{i,1} = \ldots = z_{i,r}$. This will mean that the r edges belong to $C(z_0,\ldots,z_{k-1})$. For ease of notation we show that $z_{1,1} = \ldots = z_{1,r}$. The other cases are completely identical.

An important observation at this point is that the sub-hypergraph of F induced on $V_{p_1},\ldots,V_{p_{k+1}}$ is *precisely* the k-graph S defined in Lemma 3.2 with $P_d = \{p_1,\ldots,p_{k+1}\}$. Consider any three distinct integers $j_1, j_2, j_3 \in \{1,\ldots,r\}$, such that $z_{1,j_1} \le z_{1,j_2} \le z_{1,j_3}$. By Lemma 3.2, either $z_{1,j_1} = z_{1,j_2} = z_{1,j_3}$ or there are positive integers $\beta_1,\beta_2 \le d^{3d^2}$ such that the following equation holds

$$\beta_1 z_{1,j_1} + \beta_2 z_{1,j_3} = (\beta_1+\beta_2) z_{1,j_2} \quad .$$

Assume first that for some choice of $j_1, j_2, j_3 \in \{1,\ldots,r\}$ we have $z_{1,j_1} = z_{1,j_2} = z_{1,j_3}$ and assume for simplicity that $j_1 = 1, j_2 = 2, j_3 = 3$. Consider any other $4 \le j \le r$ and assume without loss of generality that $z_{1,1} \le z_{1,j} \le z_{1,2}$. By the above, either $z_{1,1} = z_{1,2} = z_{1,j}$ or there are positive integers $\beta_1,\beta_2 \le d^{3d^2}$ such that $\beta_1 z_{1,1} + \beta_2 z_{1,2} = (\beta_1+\beta_2) z_{1,j}$. However, as by assumption $z_{1,1} = z_{1,2}$ and $\beta_1,\beta_2 > 0$ we can conclude that in this case we also have $z_{1,1} = z_{1,2} = z_{1,j}$. We thus conclude that in this case we have $z_{1,1} = z_{1,2} = \ldots = z_{1,r}$.

Assume now that none of $j_1, j_2, j_3 \in \{1,\ldots,r\}$ are such that $z_{1,j_1} = z_{1,j_2} = z_{1,j_3}$. Suppose we rename the integers $z_{1,1},\ldots,z_{1,r}$ such that $z_{1,1} \le \ldots \le z_{1,r}$. By Lemma 3.2, we have for every $2 \le i \le r-1$ that there are positive integers $\beta_{i_1},\beta_{i_2} \le d^{3d^2}$ such that

$$\beta_{i_1} z_{1,i-1} + \beta_{i_2} z_{1,i+1} = (\beta_{i_1}+\beta_{i_2}) z_{1,i} \tag{3.2}$$

holds (note that by our ordering of $z_{1,1},\ldots,z_{1,r}$ we satisfy the requirement of Lemma 3.2 that $a_i \le c_i \le b_i$). But this means that $z_{1,1},\ldots,z_{1,r}$ satisfy the (r,d^{3d^2})-gadget $\mathcal{E} = \{e_2,\ldots,e_{r-1}\}$ where

$$e_i := \beta_{i_1} x_{i-1} + \beta_{i_2} x_{i+1} = (\beta_{i_1}+\beta_{i_2}) x_i$$

(it is easy to verify that this is indeed a (r,d^{3d^2})-gadget). However, as by assumption Z is (r,d^{3d^2})-gadget-free, the integers $z_{1,1},\ldots,z_{1,r}$ cannot be distinct. Assume, without loss of generality, that $z_{1,1} = z_{1,2}$. As $z_{1,1}, z_{1,2}, z_{1,3}$ satisfy the linear equation given in (3.2) and as by assumption $z_{1,1} = z_{1,2}$ it must be the case that $z_{1,3} = z_{1,1} = z_{1,2}$. This contradicts our assumption that there is no triple of equal integers $z_{1,j_1}, z_{1,j_2}, z_{1,j_3}$.

4 Extremal Hypergraphs and Lower Bounds for $\mathcal{P}^*_D$

4.1 The main results of this section

Our main goal in this section is to prove the following lemma

Lemma 4.1. *Let D be a fixed k-graph on d vertices, which contains a copy of $T \in \mathcal{T}^k$ with r edges. Suppose we can find, for every integer m, a (r,d^{3d^2})-gadget-free subset $Z \subseteq [m/d^{k+2}]$ of size $m/f(m)$. Then, for every small enough $\varepsilon > 0$, and every large enough integer n, there is a k-graph H on n vertices that is ε-far from being induced D-free, and yet contains only $O(n^d/q(\varepsilon))$ copies of D, where $q(\varepsilon) = \max\{m : (1/f(m))^k \ge \varepsilon\}$.*

As we explain shortly, our intention is to apply the above lemma with a set Z for which the function f grows as slowly as possible.

We also need the following lemma, which follows from the *canonical graph property-tester* of Goldreich and Trevisan in [14] (see also [3]).

Lemma 4.2. *Suppose there is a k-graph on n vertices that is ε-far from satisfying $\mathcal{P}^*_D$ (or $\mathcal{P}_D$) and yet contains $O(n^d/q(\varepsilon))$ copies of D. Then the query complexity of any one-sided-error property-tester for $\mathcal{P}^*_D$ (or $\mathcal{P}_D$) is $\Omega(q(\varepsilon)^{1/d})$, where d is the size of D. In particular, if $q(\varepsilon)$ is super-polynomial in $1/\varepsilon$, then so is the query complexity of any one-sided-error property-tester for $\mathcal{P}^*_D$ (or $\mathcal{P}_D$).*

As is evident from the statement of Lemma 4.2, in order to obtain a high lower bound for testing $\mathcal{P}^*_D$, one would want to apply it to a k-graph H that is ε-far from satisfying $\mathcal{P}^*_D$ and contains $O(n^d/q(\varepsilon))$ copies of D with q growing as fast as possible. Inspecting the statement of Lemma 4.1 we see that it supplies such a k-graph, but in this case the function f should grow as slow as possible (in some sense q is f^{-1}). Note, that one can use the output of Theorem 2.3 as an input to Lemma 4.1. Finally, requiring f in Lemma 4.1 to grow slowly, means requiring the set Z in Theorem 2.3 to be as large as possible. Finally, observe that we can use the number-theoretic construction of Theorem 2.3, which supplies such a set of size $n/f(n)$ with f being sub-polynomial. This will give a super-polynomial q, and thus super-polynomial lower bounds, which are our ultimate goals. In Section 5 we indeed apply the above two lemmas, along with Lemma 3.3 and the number-theoretic construction of Theorem 2.3. In order to prove Theorem 1.2 and Theorem 1.3. The reader can find further intuition for Lemma 4.1 in the following subsection. The proofs of Lemma 4.1 and Lemma 4.2 appear in the following subsections.

4.2 Intuition for Lemma 4.1

Going back to the discussion following the statement of Lemma 3.3 we see that using Lemma 3.3 with a set Z of size $n^{1-o(1)}$ gets us very close to the requirements of Lemma 4.2, with two important differences. Returning to the example of K_4 from Section 3.3, we see that on the one hand the k-graph of Lemma 3.3 contains at most m^3 copies of K_4 on m vertices, which is far better than the $n^4/q(\varepsilon)$ copies on n vertices, which Lemma 4.2 expects to get[3]. On the other hand, however, the input k-graph to Lemma 4.2 must be ε-far from being induced K_4-free while the k-graph in Lemma 3.3 is only $m^{-o(1)}$-far from being induced K_4-free as it contains only $m^{2-o(1)}$ copies of K_4. Thus, Lemma 4.1 can be viewed as a bridge between the extremal hypergraph construction of Lemma 3.3 and the lower bounds that we can obtain using Lemma 4.2.

4.3 Proof of Lemma 4.1

We start with a key definition used in the proof of Lemma 4.1:

Definition 4.3 (Blow-up). An *s-blow-up* of a k-graph $T = (V(T), E(T))$ on t vertices is the k-graph obtained from T by replacing each vertex $v_i \in V(T)$ by an independent set I_i of size s, and each edge $(v_{i_1}, \ldots, v_{i_k}) \in E(T)$, by a complete k-partite k-graph[4] whose vertex classes are $I_{i_1}, \ldots, I_{i_k}$.

[3]The reader should note that as K_4 is complete there is no difference between having it as a subgraph or as an induced subgraph. However, this lets us keep the "intuitive" example easy to explain.

[4]A complete k-partite k-graph has as its vertex set k sets $V_1, \ldots, V_k$, and its edge set is $\{\{v_1, \ldots, v_k\} : v_1 \in V_1, \ldots, v_k \in V_k\}$.

Note, that if we take an s-blow-up of a k-graph T, we get a k-graph on st vertices that contains s^t induced copies of T, where each vertex of the copy belongs to a different blow-up of a vertex from T (simply pick one vertex from each independent set). We call these copies the *special copies* of the blow-up. As each set of k vertices in the blow-up is contained in at most s^{t-k} special copies of T, it follows that adding or removing an edge from the k-graph can destroy at most s^{t-k} special copies of T. We conclude that one must add or remove at least $s^t/s^{t-k} = s^k$ edges from the blow-up in order to destroy all its special copies of T.

Proof of Lemma 4.1. Given a small $\varepsilon > 0$, define

$$m = q(\varepsilon) \ . \tag{4.1}$$

Let $Z \subseteq [m/d^{k+2}]$ be a (r, d^{3d^2})-gadget-free, and let F be the output of Lemma 3.3, given D, T, m and Z. Recall that F has m vertices. Let H be an s-blow-up of F, where

$$s = \left\lfloor \frac{n}{|V(F)|} \right\rfloor = \left\lfloor \frac{n}{m} \right\rfloor \ . \tag{4.2}$$

If necessary, add some more isolated vertices to make sure that the number of vertices of H is precisely n. Claim 4.4 and Claim 4.6 below complete the proof of this lemma. □

Claim 4.4. *The k-graph H defined in the proof of Lemma 4.1 is ε-far from being induced D-free.*

Proof. Consider two essential copies of D in F, D_1 and D_2. By item (2) in Lemma 3.3, D_1 and D_2 share at most $k-1$ vertices $v_{i_1}, \ldots, v_{i_{k-1}}$ in F. It follows that their corresponding blow-ups in H will share at most $k-1$ independent sets $I_{i_1}, \ldots, I_{i_{k-1}}$, which replace the vertices $v_{i_1}, \ldots, v_{i_{k-1}}$ from F. Now, consider the blow-ups of D_1 and D_2 in H, denoted $\mathcal{D}_1$ and $\mathcal{D}_2$. As $\mathcal{D}_1$ and $\mathcal{D}_2$ share at most $k-1$ common independent sets, and each of the special copies of D in $\mathcal{D}_1$/$\mathcal{D}_2$ has *precisely* one vertex in each of the independent sets that replaced the vertices of F, we get that a special copy of D in $\mathcal{D}_1$ and a special copy of D in $\mathcal{D}_2$ share at most $k-1$ vertices. Thus, adding or removing an edge from H, can either destroy special copies of D that belong to $\mathcal{D}_1$, or special copies of D that belong to $\mathcal{D}_2$ (or not destroy any induced copies at all). By item (1) in Lemma 4.1 each of the essential copies of D in F is induced, thus, as we explained above, in order to destroy all the special copies of an s-blow-up of D, one needs to add or remove at least s^k edges from the blow-up. As $|Z| = m/f(m)$ we have by Lemma 3.3 item (1) that F contains $m^k/f^k(m)$ essential copies of D. Therefore, H contains $m^k/f^k(m)$ blow-ups of copies of D. We may thus infer that one has to add or delete at least

$$\frac{s^k m^k}{f^k(m)} = \frac{n^k}{f^k(m)} \geq \varepsilon n^k \tag{4.3}$$

edges in order to turn H into an induced D-free k-graph, where the inequality follows from our choice of m in (4.1) and the definition of $q(\varepsilon)$. Thus, H is ε-far from being induced D-free. □

In what follows we denote by I_v the independent set of vertices in H that replaced vertex v from F. As H is a blow-up of F it is clear that $\{v_1 \in I_{t_1}, \ldots, v_k \in I_{t_k}\}$ is an edge in H if and only if $\{t_1, \ldots, t_k\}$ is an edge in F. We remind the reader that by assumption D contains a copy of $T \in \mathcal{T}^k$, which contains $r \geq 3$ edges. We need the following simple claim:

Claim 4.5. *The number of copies of T in H is s^{k+1} times the number of copies of T in F.*

Proof. Assume $v_1 \in I_{t_1}, \dots, v_{k+1} \in I_{t_{k+1}}$ span a copy of T in H. As T is a core the sets $I_{t_1}, \dots, I_{t_{k+1}}$ are all distinct. As H is a blow-up of F we get that $t_1, \dots, t_{k+1}$ span a copy of T in F. We conclude that a copy of T in H is obtained only by picking a single vertex from each one of the $k+1$ sets $I_{t_1}, \dots, I_{t_{k+1}}$ such that $t_1, \dots, t_{k+1}$ span a copy of T in F. As H is an s-blow-up of F, we conclude that the number of copies of T in H is precisely s^{k+1} times the number of copies of T in F. □

Claim 4.6. *The k-graph H defined in the proof of Lemma 4.1 has $O(n^d/q(\varepsilon))$ copies of D.*

Proof. Note, that as D contains at least one copy of T, and each copy of T belongs to at most $\binom{n}{d-k-1} \leq n^{d-k-1}$ copies of D, it is enough to show that H contains at most $n^{k+1}/q(\varepsilon)$ copies (induced or not) of T. By Claim 4.5, the number of copies of T in H is precisely s^{k+1} times the number of copies of T in F. By item (3) in Lemma 3.3 each copy of T belongs to one of the essential copies of D. As each copy of D can contain at most $\binom{d}{k+1} \leq d^{k+1}$ copies of T, and F contains *precisely* $m^k/f^k(m)$ essential copies of D, we get that H contains at most

$$\frac{d^{k+1} \cdot m^k \cdot s^{k+1}}{f^k(m)} = \frac{d^{k+1} \cdot m^k \cdot n^{k+1}}{f^k(m) \cdot m^{k+1}} \leq \frac{d^{k+1} \cdot n^{k+1}}{m} = O(n^{k+1}/q(\varepsilon)) \tag{4.4}$$

copies of T, where the first equality is due to our choice of s in (4.2), and in the last equality we used the definition of m in (4.1). □

4.4 Proof of Lemma 4.2

We need the following result of [14], mentioned already in [3].

Lemma 4.7. **([3],[14])** *If there exists an ε-tester for a graph property that makes q queries, then there exists such an ε-tester that makes its queries by uniformly and randomly choosing a set of $2q$ vertices, querying all their pairs and then accepting/rejecting according to the graph induced by the sample. In particular, it is a non-adaptive ε-tester making $\binom{2q}{2}$ queries.*

Restating the above, by (at most) squaring the query complexity, we can assume without loss of generality that a property-tester works by sampling a set of vertices of size $q(\varepsilon, n)$ and accepting/rejecting according to the graph spanned by the set. In [14] the authors measure the query complexity of a property tester by counting the number of edge queries. As we measure query complexity by the number of vertices sampled, assuming we always query all possible edges within the sample, we infer from Lemma 4.7 that we can simply assume that the property tester first samples a set of vertices, queries about all the edges, and then proceeds to perform some other computation. Also, the proof of Lemma 4.7 was described in [14] for graphs, however, precisely the same argument carries over to k-graphs. We need the following simple observations:

Claim 4.8. *Suppose Q is a k-graph on q vertices containing no induced copy of some k-graph D. Then, for any $n > q$ there is a k-graph H on n vertices, which contains Q as an induced subgraph, and does not contain D as an induced subgraph.*

Proof. It is clearly enough to show that there is such a k-graph on $q+1$ vertices. Let d denote the number of vertices of D. Suppose first that D has no vertex of degree $\binom{d-1}{k-1}$ (i.e. a vertex that forms an edge with all the other subsets of $k-1$ vertices). In this case, if we add to Q a vertex and connect it to all the $\binom{q}{k-1}$ sets of $k-1$ vertices of Q, we are guaranteed that the new k-graph spans no induced copy of D. Suppose now that D has no isolated vertex. In this case we add to Q an isolated vertex and thus guarantee that the new k-graph spans no induced copy of D. The only case left is that D has an isolated vertex and a vertex of degree $\binom{d-1}{k-1}$, which is impossible. □

By Theorem 4.7 we can assume that a property-tester for $\mathcal{P}^*_D$ works by inspecting a random subset of vertices. The following claim shows that such a one-sided-error property-tester can reject an input only if it finds an induced copy of D in the sample of vertices.

Claim 4.9. *Let D be a some k-graphs, and let A be a one-sided-error tester for $\mathcal{P}^*_D$ with query complexity $q(\varepsilon,n)$. If for some $\varepsilon_0 > 0$ and n, after A samples a set of vertices of size $q(\varepsilon_0,n)$, the k-graph induced by the sample is induced D-free, then A must accept the input.*

Proof. Fix any n and $\varepsilon_0 > 0$ and suppose that when we execute A on a k-graph H' of size n with $\varepsilon = \varepsilon_0$, and the sample of vertices spans a k-graph Q (of size $q(\varepsilon_0,n)$) that is induced D-free, the algorithm still rejects the input. By Claim 4.8 there is a k-graph H on n vertices that is induced D-free and contains an induced copy of Q. Suppose we execute A on H with $\varepsilon = \varepsilon_0$. As H and H' are of the same size n, when given H as input the algorithm samples a set of vertices of size $q(\varepsilon_0,n) = |V(Q)|$. As we assume that when given Q the algorithm rejects, we get that there is a nonzero probability that A will reject H, contradicting the assumption that it has one-sided error. □

Proof of Lemma 4.2. We start with the proof of $\mathcal{P}^*_D$. As the algorithm is a one-sided-error algorithm, we get from Claim 4.9 that it can report that H is not induced D-free only if it finds an induced copy of D in it. Observe, that if the tester picks a random subset of x vertices, and an input k-graph contains only $O(n^d/q(\varepsilon))$ copies (induced or not) of D, then the expected number of induced copies of D spanned by x is $O(x^d/q(\varepsilon))$, which is $o(1)$ unless $x = \Omega(q(\varepsilon)^{1/d})$. By Markov's inequality, unless $x = \Omega(q(\varepsilon)^{1/d})$, the tester finds an induced copy of D with negligible probability.

The proof for $\mathcal{P}_D$ is similar. What we need is a version of Claim 4.8 but with respect to non-induced sub-hypergraphs. But here the proof is even simpler: If we have a k-graph Q on q vertices that has no copy of a k-graph D, we can construct a k-graph on $q+1$ vertices that contains an induced copy of Q but no copy of D, simply by adding an isolated vertex to Q. Note, that here we assume that D has no isolated vertices. Clearly when testing $\mathcal{P}_D$ we may assume that this is the case, because if D' is obtained from D by removing an isolated vertex, then any k-graph on at least $|V(D)|$ vertices, satisfies $\mathcal{P}_{D'}$ iff it satisfies $\mathcal{P}_D$. Thus for k-graphs of size at least $|V(D)|$ testing $\mathcal{P}_{D'}$ is equivalent to testing $\mathcal{P}_D$, hence it is enough to prove a lower bound for one of them. □

5 Proofs of Theorem 1.2 and Theorem 1.3

5.1 A lower bound for (almost) all k-graphs

In this section we apply the number-theoretic construction of Theorem 2.3, the construction of the extremal k-graphs of Lemma 3.3 as well as Lemma 4.1 and Lemma 4.2 in order to prove Theorem 1.2.

We first need the following claim in which we denote by $\overline{D}$ the complement of D, that is, a k-graph that contains an edge if and only if D does not. We also call a k-graph D, *strongly* $\mathcal{T}^k$-free, if neither D nor $\overline{D}$ contains a copy of $\mathcal{T}^k$.

Claim 5.1. *There are no strongly $\mathcal{T}^3$-free 3-graphs on at least 7 vertices. For any $k > 3$, there are no strongly $\mathcal{T}^k$-free k-graphs on at least $k+1$ vertices.*

Proof. The case of $k > 3$ is simple. As in this case $\binom{k+1}{k} \geq 5$, on *any* set of $k+1$ vertices either D or $\overline{D}$ spans a copy of $\mathcal{T}^k$. For the case of $k = 3$, observe that D is strongly $\mathcal{T}^3$-free, if and only if each set of 4 vertices spans precisely 2 edges. Fixing any set of 7 vertices, this set must span precisely $\binom{7}{4}2/4$ edges, where we count the number of 4-sets, multiply by 2 as each 4-set by assumption spans 2 edges, and divide by 4, because we count each edge 4 times. Since this is not an integer it is impossible. Thus, on *any* set of 7 vertices either D or $\overline{D}$ spans a copy of $\mathcal{T}^3$. □

Proof of Theorem 1.2. Let D be a fixed k-graph on d vertices. A simple yet crucial observation is that for every k-graph D, testing $\mathcal{P}^*_D$ is equivalent to testing $P^*_{\overline{D}}$. Note, that this relation does not hold for testing $\mathcal{P}_D$. It follows that in order to prove a lower bound for testing $\mathcal{P}^*_D$, we may prove a lower bound for testing $P^*_{\overline{D}}$. By Claim 5.1 all the k-graphs in the statement of Theorem 1.2 (besides some 3-graphs on 4,5 and 6 vertices. See comment below on how to deal with them) are not strongly $\mathcal{T}^k$-free, hence we may assume that D contains a copy of $T \in \mathcal{T}^k$ with at least 3 edges. By Theorem 2.3 (with $k = 2$ and $h = d^{3d^2}$), there is a $(3, d^{3d^2})$-gadget-free set $Z \subseteq m/d^{k+2}$ of size $(m/d^{k+2})/e^{c\sqrt{\log(m/d^{k+2})}} = m/e^{c\sqrt{\log m}}$ for an appropriate $c = c(d)$. This means that we can use Lemma 4.1 with $f(m) = e^{c\sqrt{\log m}}$. It is easy to check that in this case $q(\varepsilon)$ in the statement of Lemma 4.1 satisfies

$$q(\varepsilon) \geq \left(\frac{1}{\varepsilon}\right)^{c' \log 1/\varepsilon} , \tag{5.1}$$

for an appropriate constant $c' = c'(d)$. By Lemma 4.1 we get a k-graph that is ε-far from being induced D-free, and contains only $O(n^d/q(\varepsilon))$ copies of D. By Lemma 4.2 the query complexity of any one-sided-error property-tester for $\mathcal{P}^*_D$ can be bounded from below by $q(\varepsilon)^{1/d}$, which is (5.1), with c' replaced by c'/d. □

It is worth mentioning that there are strongly $\mathcal{T}^3$-free 3-graphs on 4,5, and 6 vertices. For 4 vertices there is a unique such 3-graph, which is $D_{3,2}$ (which contains 2 edges) mentioned in the statement of the Theorem 1.3. This is the only k-graph for which we do not know whether $\mathcal{P}^*_D$ is easily testable. For 5 vertices, it is easy to verify that the only strongly $\mathcal{T}^3$-free 3-graph has the edges $\{(1,2,3), (2,3,4), (3,4,5), (4,5,1), (5,1,2)\}$. This 3-graph is better understood if one considers the 5 vertices on a cycle, and the edges as all triples consisting of three consecutive vertices on the cycle. In what follows we call it $D_{3,5}$. It is easy to check that $D_{3,5}$ is a hyper-cycle (see Definition 1.6), thus we can prove a version of Lemma 4.1 (namely, constructing a k-graph, which is ε-far from being $D_{3,5}$-free and yet contains only $O(n^5/(1/\varepsilon)^{c \log 1/\varepsilon})$ copies of $D_{3,5}$) that instead of using Lemma 3.3 and Theorem 2.3, uses Lemma 6.1 and Lemma 6.7, which are proved below. The details are very similar. For 6 vertices there are also some 3-graphs that are strongly $\mathcal{T}^3$-free, however, every 5 vertices of such a 3-graph must span a copy of $D_{3,5}$ thus we can again use the same arguments as for $D_{3,5}$ to prove that any such 3-graph is not easily testable.

5.2 The improved lower bound

Proof of Theorem 1.3. Observing, as in the proof of Theorem 1.2, that we may either prove a lower bound for D or $\overline{D}$, we recall that by Ramsey's Theorem, for any integer k there is an integer $r(k)$ such that for any k-graph D on at least $r(k)$ vertices, either D or $\overline{D}$ contains a copy of F^k. Hence, we may assume that D contains a copy of F^k, which is a member of $\mathcal{T}^k$ with $k+1$ edges. By Theorem 2.3, there is a $(k+1, d^{3d^3})$-gadget-free set $Z \subseteq m/d^{k+2}$ of size

$$|Z| \geq (m/d^{k+2})/e^{c'(\log(m/d^{k+2}))^{1/\lfloor \log 2k \rfloor}} = m/e^{c(\log m)^{1/\lfloor \log 2k \rfloor}}$$

for an appropriate $c = c(d,k)$. This means that we can use Lemma 4.1 with $f(m) = e^{c(\log m)^{1/\lfloor \log 2k \rfloor}}$. It is easy to check that in this case $q(\varepsilon)$ in the statement of Lemma 4.1 satisfies

$$q(\varepsilon) \geq \left(\frac{1}{\varepsilon}\right)^{c'(\log 1/\varepsilon)^{\lfloor \log k \rfloor}}, \tag{5.2}$$

for an appropriate constant $c' = c'(d)$. By Lemma 4.1 we get a k-graph, which is ε-far from being induced D-free, and contains only $O(n^d/q(\varepsilon))$ copies of D. By Lemma 4.2 the query complexity of any one-sided-error property-tester for $\mathcal{P}^*_D$ can be bounded from below by $q(\varepsilon)^{1/d}$, which is (5.2), with c' replaced by c'/d. ☐

Note, that though the statement of Theorem 1.3 states the improved lower bounds only for k-graphs on at least $r(k)$ vertices, it should be clear that the same lower bound also applies to any k-graph on less than $r(k)$ vertices such that either the k-graph or its complement spans a copy of F^k. This, in particular, applies to F^k itself, thus, as mentioned after the statement of Theorem 1.3, we indeed get an improvement on the lower bound for testing $\mathcal{P}^*_{F^k}$ from [17]. It is worth mentioning that if one is willing to replace $\lfloor \log k \rfloor$ with $\lfloor \log \lceil k/2+1 \rceil \rfloor$ in the statement of Theorem 1.3, then one can obtain this slightly weaker lower bound for **any** k-graph on at least $k+1$ vertices, instead of k-graphs on at least $r(k)$ vertices. One just has to note that for any set of $k+1$ vertices, either the k-graph or its complement spans at least $\lceil k/2+1 \rceil$ edges. One then proceeds as in the proof of Theorem 1.3 by taking a set Z, which is $(\lceil k/2+1 \rceil, d^{3d^2})$-gadget-free instead of $(k+1, d^{3d^2})$-gadget-free.

6 More on Linear Equations and Extremal Hypergraphs

In this section we prove Theorem 1.7. Analogously to our proof technique for $\mathcal{P}^*_D$, the first step in the proof of Theorem 1.7 is to show that given a hyper-cycle $D = (V,E)$ on d vertices we can construct a k-graph that contains many copies of D such that from each copy of D we can infer a certain linear equation. The main idea, as in Lemma 3.2, is to give an algebraic construction of such a graph, but as we explain below, in this case we have some additional difficulties.

Let m be an integer, $Z \subseteq [m]$ and D a hyper-cycle of size d, whose vertices are numbered $\{1,\dots,d\}$ as in the definition of a hyper-cycle. We define a k-graph $F = F(D,Z)$ as follows: the vertex set of F consists of d pairwise disjoint sets of vertices $V_1,\dots,V_d$, where, with a slight abuse of notation, we think of each of these sets as being the set of integers $1,\dots,d^{k+1}m$. We define the edge set of F by specifying the edge sets of $|Z|^k$ copies of D that we put in F. For every set of (not necessarily distinct) integers $z_0,\ldots,z_{k-1} \in Z$, we define a copy of D denoted $C = C(z_0,\ldots,z_{k-1})$: As the vertex set of C, we choose d vertices $v_1 \in V_1,\ldots,v_d \in V_d$, where for $1 \le t \le d$ we choose $v_t = E(z_0,\ldots,z_{k-1},t)$, and E is the function defined in (3.1). Note, that for any choice of $z_0,\ldots,z_{k-1} \in Z$ we have $E(z_0,\ldots,z_{k-1},t) \in [d^{k+1}m]$, thus the vertices "fit" into the sets $V_1,\ldots,V_d$. As for the edges of C, we simply regard the vertices $v_1 \in V_1,\ldots,v_d \in V_d$ as if they were the vertices $1,\ldots,d$ in D, namely, if $(t_1,\ldots,t_k) \in E(D)$, we put in F an edge that contains the vertices

$$E(z_0,\ldots,z_{k-1},t_1) \in V_{t_1},\ E(z_0,\ldots,z_{k-1},t_2) \in V_{t_2},\ \ldots\ ,E(z_0,\ldots,z_{k-1},t_k) \in V_{t_k} \ .$$

The main technical step in this section is the proof of the following lemma, whose role in the proof of Theorem 1.7 is analogous to the role of Lemma 3.2 in the proof of Theorem 1.2 and Theorem 1.3.

Lemma 6.1. *Let m be an arbitrary integer, $Z \subseteq [m]$ and D a hyper-cycle on d vertices. Construct $F = F(D,Z)$ as above. Suppose $v_1 \in V_1,\ldots,v_d \in V_d$ span a copy of D, with v_t playing the role of vertex t in D. Suppose that for $1 \le i \le d-k+2$ edge e_i belongs to $C(z_{0,i},\ldots,z_{k-1,i})$. Then, for every $1 \le j \le k-1$ there are* **positive** *integers $a_1,\ldots,a_{d-k+1} \le c = c(d)$ such that*

$$a_1 \cdot z_{j,1} + a_2 \cdot z_{j,2} + \ldots + a_{d-k+1} \cdot z_{j,d-k+1} = (a_1 + a_2 + \ldots + a_{d-k+1}) \cdot z_{j,d-k+2} \ .$$

In order to apply Lemma 6.1, we need another notion of linear equations suitable for it, which we formulate as follows:

Definition 6.2 ((k,h)-linear-free). A set of integers $Z \subseteq [m] = \{1,2,\ldots,m\}$ is called *(k,h)-linear-free* if for every k **positive** integers $a_1,\ldots,a_k \le h$, the only solution of the equation

$$a_1 z_1 + \ldots + a_k z_k = (a_1 + \ldots + a_k) z_{k+1} \ , \tag{6.1}$$

which uses $k+1$ integers from Z satisfies $z_1 = z_2 = \ldots = z_{k+1}$.

In simple words, if Z is (k,h)-linear-free, then whenever $a_1,\ldots,a_k \le h$, the only solution to (6.1) using integers from Z, is one of the $|Z|$ trivial solutions. Similar to our proof technique of Theorem 1.2 and Theorem 1.3, in this case we will also need a dense (k,h)-linear-free sets of integers, with which we will apply Lemma 6.1.

The main difficulty in proving Lemma 6.1 is two fold; While we still have to show that we can extract a linear combination of the integers, as we did in Lemma 3.2, we are faced with the following problem; suppose we manage to extract a linear equation but it is of the form $z_1 + z_2 - z_3 = z_4$. In Lemma 3.2 this was not an issue, as in that lemma the required equation only relates 3 integers, thus if we get an equation of the form, say, $3a - 2b = c$, we can simply "shift" $2b$ to the other side and get the required equation. This is not possible in our case. The problem is even more serious; as we mentioned above (and analogously to our proof technique for $\mathcal{P}^*_D$), our ultimate goal will be to apply Lemma 6.1 with a (k,h)-linear-free set of size $m^{1-o(1)}$. However, it follows from the pigeon-hole principle that the largest size of a subset of $[m]$ without solutions to $z_1 + z_2 - z_3 = z_4$ is $O(\sqrt{m})$. Thus, we must make sure that all the coefficients in the linear equation we extract are positive. One may also ask, why we cannot prove our lower bounds for $\mathcal{P}_D$ by using only linear equations with 3 unknowns, like we use for $\mathcal{P}^*_D$. The main reason for that is that for $\mathcal{P}^*_D$ we can prove a lower bound either for D or its complement, and one of them must contain a copy of $\mathcal{T}^k$. For $\mathcal{P}_D$, however, we cannot use this reasoning and have to deal with D itself, which does not necessarily contain a copy of $\mathcal{T}^k$.

The proof of Theorem 1.7 will follow by using Lemma 6.1 together with arguments similar to those used in the proofs of Lemma 3.3, Lemma 4.1 and Lemma 4.2. The proof Lemma 6.1 appears in the following subsection, and the proof of Theorem 1.7 appears in Section 6.2.

6.1 Proof of Lemma 6.1

For the proof of Lemma 6.1 we need the following simple observation:

Claim 6.3. *For a given set of $p \le r$ distinct integers $t_1,\dots,t_p$ bounded by r, let A be the matrix $(A)_{i,j} = t_i^{p+1-j} - (t_i-1)^{p+1-j}$ $(1 \le i,j \le p)$. Then, there is a nonzero integer vector v, all of whose entries are bounded (in absolute value) by r^{2r}, such that for $1 \le i \le p-1$ $(Av)_i = 0$, while $(Av)_p > 0$.*

Proof. As the integers $t_1,\dots,t_p$ are distinct, the Vandermonde matrix $(V)_{i,j} = t_i^{j-1}$ is invertible. As A can be obtained from V by rank preserving operations, A is also invertible. By Claim 2.7 there is a nonzero integer vector v, all of whose entries are bounded by $(r^2p)^{p/2} \le (rp)^p \le r^{2r}$, such that for $1 \le i \le p-1$ we have $(Av)_i = 0$. As A is invertible and v is non zero, it cannot be the case that $(Av)_p = 0$, and if $(Av)_p < 0$ we can replace v by $-v$. □

As a first step towards the proof of Lemma 6.1 we prove the following claim.

Claim 6.4. *Let m be an arbitrary integer, $Z \subseteq [m]$ and D a hyper-cycle on d vertices. Construct $F = F(D,Z)$ as in Lemma 6.1, and denote by $\overline{i}$ the vector $(i,i^2,\dots,i^{k-1})$ and by $\overline{z_i}$ the vector $(z_{1,i},z_{2,i},\dots,z_{k-1,i})$. Then the following equation holds*

$$\overline{z_1}\cdot(\overline{2}-\overline{1})+\ldots+\overline{z_{d-k+1}}\cdot(\overline{d-k+2}-\overline{d-k+1}) = \overline{z_{d-k+2}}\cdot(\overline{d-k+2}-\overline{1}) \ . \tag{6.2}$$

Also, for every $1 \le i \le d-k+1$ and $i+1 \le t \le i+k-2$ the following equation holds

$$\overline{z_{i+1}}\cdot(\overline{t+1}-\overline{t}) - \overline{z_i}\cdot(\overline{t+1}-\overline{t}) = 0 \ . \tag{6.3}$$

Proof. Let $v_1 \in V_1,\dots,v_d \in V_d$ be d vertices spanning a copy of D, with $v_i \in V_i$ playing the role of vertex i in D. For every $1 \le i \le d-k+1$ consider the vertices $v_i \in V_i$ and $v_{i+1} \in V_{i+1}$ and recall that by the definition of a hyper-cycle they belong to $e_i \in C(z_{0,i},\dots,z_{k-1,i})$. If we regard v_i and v_{i+1} as integers we get from the definition of F that $v_i = E(z_{0,i},\dots,z_{k-1,i},i)$ and that $v_{i+1} = E(z_{0,i},\dots,z_{k-1,i},i+1)$. From the definition of E in (3.1) this means that (note that $z_{0,i}$ disappears)

$$v_{i+1}-v_i = z_{1,i}\cdot((i+1)-i)+z_{2,i}\cdot((i+1)^2-i^2)+\ldots+z_{k-1,i}\cdot((i+1)^{k-1}-i^{k-1}) \ . \tag{6.4}$$

As in the statement of the claim, let the vector $\overline{i}$ denote $(i,i^2,\dots,i^{k-1})$ and let the vector $\overline{z_i}$ denote $(z_{1,i},z_{2,i},\dots,z_{k-1,i})$. Therefore, we can write for every $1 \le i \le d-k+1$ the vector equation

$$v_{i+1}-v_i = \overline{z_i}\cdot(\overline{i+1}-\overline{i}) \ . \tag{6.5}$$

$$
\begin{aligned}
z_{1,1}+3z_{2,1}+7z_{3,1}+z_{1,2}+5z_{2,2}+19z_{3,2}+z_{1,3}+7z_{2,3}+37z_{3,3} &= 3z_{1,4}+15z_{2,4}+63z_{3,4}\\
z_{1,1}+5z_{2,1}+19z_{3,1}-z_{1,2}-5z_{2,2}-19z_{3,2} &= 0\\
z_{1,1}+7z_{2,1}+37z_{3,1}-z_{1,2}-7z_{2,2}-37z_{3,2} &= 0\\
z_{1,2}+7z_{2,2}+37z_{3,2}-z_{1,3}-7z_{2,3}-37z_{3,3} &= 0\\
z_{1,2}+9z_{2,2}+61z_{3,2}-z_{1,3}-9z_{2,3}-61z_{3,3} &= 0\\
z_{1,3}+9z_{2,3}+61z_{3,3} &= z_{1,4}+9z_{2,4}+61z_{3,4}\\
z_{1,3}+11z_{2,3}+191z_{3,3} &= z_{1,4}+11z_{2,4}+191z_{3,4}
\end{aligned}
$$

Figure 1: The linear equations (6.2), $\mathcal{E}_{1,2},\mathcal{E}_{1,3},\mathcal{E}_{2,3},\mathcal{E}_{2,4},\mathcal{E}_{3,4},\mathcal{E}_{3,5}$ when $d=6$ and $k=4$.

As e_{d-k+2} contains the vertices $v_{d-k+2}\in V_{d-k+2},\dots,v_d\in V_d$ we have for every $d-k+2\le i\le d-1$

$$v_{i+1}-v_i=\overline{z_{d-k+2}}\cdot(\overline{i+1}-\overline{i}) \quad . \tag{6.6}$$

Summing (6.5) for $1\le i\le d-k+1$ and (6.6) for $d-k+2\le i\le d-1$ we obtain

$$v_d-v_1=\overline{z_1}\cdot(\overline{2}-\overline{1})+\ldots+\overline{z_{d-k+1}}\cdot(\overline{d-k+2}-\overline{d-k+1})+\overline{z_{d-k+2}}\cdot(\overline{d}-\overline{d-k+2}) \quad . \tag{6.7}$$

As e_{d-k+2} contains the vertices $v_1\in V_1$ and $v_d\in V_d$, we also have by the same reasoning

$$v_d-v_1=\overline{z_{d-k+2}}\cdot(\overline{d}-\overline{1}) \quad . \tag{6.8}$$

Combining (6.7) and (6.8) we obtain (6.2).

In order to obtain the other equations, for any $1\le i\le d-k+1$ consider edge e_i and recall that it contains the vertices $i,\dots,i+k-1$. Note that for every $i+1\le t\le i+k-2$ vertices t and $t+1$ belong to both e_i and e_{i+1}. By the same reasoning used to obtain (6.4) and (6.5) we can write for every $i+1\le t\le i+k-2$

$$v_{t+1}-v_t=\overline{z_i}\cdot(\overline{t+1}-\overline{t}) \tag{6.9}$$

$$v_{t+1}-v_t=\overline{z_{i+1}}\cdot(\overline{t+1}-\overline{t}) \tag{6.10}$$

Combining these equations we get (6.3) for every $i+1\le t\le i+k-2$, thus completing the proof. □

For the rest of the proof let us use the following notation: for every $i+1\le t\le i+k-2$ denote by $\mathcal{E}_{i,t}$ the equation of (6.3). Note, that for every $1\le i\le d-k+1$ we have $k-2$ equations $\mathcal{E}_{i,t}$. To illustrate the main ideas of the proof the reader may want to consider the special case where $d=6$ and $k=4$ depicted in Figure 1.

We also need the following claim. For its proof, the reader may find it useful to refer to the example given in Figure 1.

Claim 6.5. *For every $1 \le i \le d-k+1$ there is a linear combination of* (6.2) *and equations $\mathcal{E}_{i,i+1},\dots,\mathcal{E}_{i,i+k-2}$ with integer coefficients, in which the coefficient of $z_{i,1}$ is positive, while the coefficients of $z_{i,2},\dots,z_{i,k-1}$ vanish.*

Proof. Let $\alpha_1,\dots,\alpha_{k-1}$ denote the unknown coefficients of (6.2) and $\mathcal{E}_{i,i+1},\dots,\mathcal{E}_{i,i+k-2}$, respectively, in the linear combination, which we seek. Suppose we write $k-1$ linear equations $e_1,\dots,e_{k-1}$ in unknowns $\alpha_1,\dots,\alpha_{k-1}$, where equation e_i requires the coefficient of $z_{i,1}$ to vanish in the linear combination of (6.2), $\mathcal{E}_{i,i+1},\dots,\mathcal{E}_{i,i+k-2}$ with coefficient $\alpha_1,\dots,\alpha_{k-1}$. Observing the coefficients of $z_{1,i},\dots,z_{k-1,i}$ in (6.2) and in $\mathcal{E}_{i,i+1},\dots,\mathcal{E}_{i,i+k-2}$ it is easy to see that the entries of the $(k-1)\times(k-1)$ matrix A, whose i^{th} row contains equation e_i satisfies the properties of Claim 6.3. We can now take the entries of the vector v, whose existence is guaranteed by Claim 6.3, to be the required integer coefficients $\alpha_1,\dots,\alpha_{k-1}$. ☐

Proof of Lemma 6.1. We first observe that (6.2) is an equation in $z_{j,i}$, where for $1 \le j \le k-1$ and $1 \le i \le d-k+1$ we have $z_{j,i}$ on the left hand side of the equation, and for every $1 \le j \le k-1$ we have $z_{j,d-k+2}$ on the right hand side. Furthermore, all the coefficients in this equation are positive. Finally, for every $1 \le j \le k-1$ the sum of the coefficients of $z_{j,1},\dots,z_{j,d-k+1}$ is equal to $(d-k+2)^j-1$, which is precisely the coefficient of $z_{j,d-k+2}$. It thus follows that (6.2) is the **sum** of the $k-1$ equations that we need to obtain in order to prove the lemma. In order to simplify the notation we now turn to show how to obtain the linear equation relating $z_{1,1},\dots,z_{1,d-k+2}$. The other cases are completely identical.

To simplify the rest of the proof, when we later refer to *fixing i* we mean obtaining a linear equation in which $z_{2,i},\dots,z_{k-1,i}$ do not appear, while the coefficient of $z_{1,i}$ is positive. Our main idea of extracting from (6.2) the required linear equation relating $z_{1,1},\dots,z_{1,d-k+2}$ is the following: For $1 \le i \le d-k+2$, equation (6.2) contains the variables $z_{1,i},\dots,z_{k-1,i}$, while we want an equation in which only $z_{1,i}$ appears. We thus need to fix i for every $1 \le i \le d-k+2$. By Claim 6.5 we know that for every $1 \le i \le d-k+1$ we can find a linear combination of (6.2) and $\mathcal{E}_{i,i+1},\dots,\mathcal{E}_{i,i+k-2}$, which fixes i. The main problem is that we need a linear combination which simultaneously fixes any i. Suppose we first use Claim 6.5 in order to obtain a new equation, denoted $\mathcal{E}$, which fixes $i=1$. We would now want to reapply Claim 6.5 in order to fix $i=2$. The only difficulty is that we would now want to take a linear combination of $\mathcal{E}_{2,3},\dots,\mathcal{E}_{2,k}$ with $\mathcal{E}$, and not with (6.2) as taking a linear combination with (6.2) might "bring back" $z_{2,1},\dots,z_{k-1,1}$.

However, it is easy to see that we can also find a linear combination of $\mathcal{E}_{2,3},\dots,\mathcal{E}_{2,k}$ and $\mathcal{E}$, which fixes $i=2$. By Claim 6.5, we know that there is a linear combination of $\mathcal{E}_{2,3},\dots,\mathcal{E}_{2,k}$ and (6.2), which fixes $i=2$. Consider now the coefficients of $z_{1,2},\dots,z_{k-1,2}$ in equations (6.2), $\mathcal{E}_{1,2},\dots,\mathcal{E}_{1,k-1}$ and $\mathcal{E}_{2,3},\dots,\mathcal{E}_{2,k}$. Note, that the coefficients, which appear in equations (6.2), $\mathcal{E}_{1,2},\dots,\mathcal{E}_{2,k-2}$ also appear in equations (6.2), $\mathcal{E}_{2,3},\dots,\mathcal{E}_{2,k}$. To be more precise, the coefficients of $z_{1,2},\dots,z_{k-1,2}$ in equation $\mathcal{E}_{1,2}$ are precisely the coefficients of $z_{1,2},\dots,z_{k-1,2}$ in (6.2) and for every $3 \le i \le k-1$ the coefficients of $z_{1,2},\dots,z_{k-1,2}$ in equation $\mathcal{E}_{1,i}$ are precisely the coefficients of $z_{1,2},\dots,z_{k-1,2}$ in equation $\mathcal{E}_{2,i-1}$. Thus, as $\mathcal{E}$ is a linear combination of (6.2) and $\mathcal{E}_{1,2},\dots,\mathcal{E}_{2,k-1}$ we infer that if there is a linear combination of (6.2) and $\mathcal{E}_{2,3},\dots,\mathcal{E}_{2,k}$, which fixes $i=2$, then there must be such a linear combination of $\mathcal{E}$ and $\mathcal{E}_{2,3},\dots,\mathcal{E}_{2,k}$. It is finally important to note that as $z_{1,1},\dots,z_{1,k-1}$ do not appear in equations $\mathcal{E}_{2,3},\dots,\mathcal{E}_{2,k}$ then in the new linear equation $i=1$ remains fixed.

Note that the above argument can be generalized to any $2 \le i \le d-k+1$ as equations $\mathcal{E}_{i,i+1},\dots,\mathcal{E}_{i,i+k-2}$ do not contain the unknowns $z_{1,p},\dots,z_{k-1,p}$ for any $p < i$, and the coefficients of $z_{i,1},\ldots,z_{i,k-1}$ appearing in (6.2) and $\mathcal{E}_{i-1,i},\ldots,\mathcal{E}_{i-1,i+k-3}$ also appear in equations (6.2) and $\mathcal{E}_{i,i+1},\ldots,\mathcal{E}_{i,i+k-2}$. Hence, we can apply an iterative procedure, where in the i^{th} step we add to (6.2) an appropriate linear combination of equations $\mathcal{E}_{i,i+1},\ldots,\mathcal{E}_{i,i+k-2}$, which fixes i. Moreover, later iterations of this procedure will not change the coefficients of $z_{1,p},\ldots,z_{k-1,p}$ for any $p<i$. In particular, if in iteration p we fixed $i=p$, then we will also have this property at the end of the process. We have thus established that for $1\le i\le d-k+1$ our process obtains in iteration i a linear combination in which for every $p\le i$ the coefficient of $z_{1,p}$ is positive, while the coefficients of $z_{2,p},\ldots,z_{k-1,p}$ have vanished. We now observe that as both in (6.2) and (6.3) the coefficient of $z_{i,d-k+2}$ is equal to the sum of the coefficients of $z_{i,1},\ldots,z_{i,d-k-1}$, it must be the case that after iteration $d-k+1$ the coefficient of $z_{1,d-k+2}$ is positive while the coefficients of $z_{2,d-k+2},\ldots,z_{k-1,d-k+2}$ have vanished, thus $i=d-k+2$ is also fixed. This means that we have obtained the required equation relating $z_{1,1},z_{1,2},\ldots,z_{1,d-k+2}$. As for the size of the integers in this linear equation, note that the coefficients of (6.2) and (6.3) are bounded by $d^k\le d^d$. As we apply the above iterative process $d-k+1<d$ times, Claim 6.3 guarantees that when we are done the coefficients are bounded by a function of d only.

□

Corollary 6.6. *For every d, there is $c=c(d)$ such that if we construct the k graph F in Lemma 6.1 with a $(d-k+2,c)$-linear-free set Z, then F contains precisely $|Z|^d$ copies of D spanned by vertices $v_1\in V_1,\ldots,v_d\in V_d$, with v_t playing the role of vertex t in D.*

Proof. The main idea is simply to show that the only such copies of D belong to the same copy of D defined for some choice of integers $z_0,\ldots,z_{k-1}\in Z$. Consider any copy of D spanned by vertices $v_1\in V_1,\ldots,v_d\in V_d$, with v_t playing the role of vertex t in D. Suppose for every $1\le i\le d-k+2$ edge e_i of D belongs to $C(z_{0,i},\ldots,z_{k-1,i})$. Lemma 6.1 guarantees that for every $1\le j\le k-1$ there are positive integers $a_1,\ldots,a_{d-k+1}\le c=c(d)$ such that the following equation is satisfied

$$a_1\cdot z_{j,1}+a_2\cdot z_{j,2}+\ldots+a_{d-k+1}\cdot z_{j,d-k+1}=(a_1+a_2+\ldots+a_{d-k+1})\cdot z_{j,d-k+2}\quad .$$

Therefore, if we use a set Z, which is $(d-k+2,c)$-linear-free it must be the case that for every $1\le j\le k-1$, we have $z_{j,1}=z_{j,2}=\ldots=z_{j,d-k+2}$. To complete the proof we just have to show that we also have $z_{0,1}=z_{0,2}=\ldots=z_{0,d-k+2}$ as this will imply that all the edges of D belong to the same copy defined using $z_{0,1},z_{1,1},\ldots,z_{k-1,1}$. To show this we observe that for every $2\le t\le d-k+2$, vertex $v_t\in V_t$ is common to both e_{t-1} and e_t. This means that

$$E(z_{0,t-1},\ldots,z_{k-1,t-1},t)=v_t=E(z_{0,t},\ldots,z_{k-1,t},t)\quad .$$

As we already know that for every $1\le j\le k-1$ we have $z_{j,i}=z_{j,i+1}$, the above equation implies that $z_{0,t-1}=z_{0,t}$ holds for every $2\le t\le d-k+2$, thus completing the proof. □

6.2 Proof of Theorem 1.7

Given Lemma 6.1, the proof of Theorem 1.7 follows by going along the lines of the proofs of Lemma 3.3 and Lemma 4.1, with one key difference, which we shall explain. In order to avoid repeating the same arguments we will just sketch them, while assuming that the reader is familiar with the proofs of Lemma 3.3 and Lemma 4.1. As in Lemma 4.1, we will also need a large set of integers that does not satisfy linear equations similar to the one we extract by using Lemma 6.1. We will thus need the following:

Lemma 6.7. *For every k and h there is $c = c(k,h)$, such that for every n, there is a (k,h)-linear-free subset $Z \subset [n] = \{1,2,\ldots,n\}$ of size at least*

$$|Z| \geq \frac{m}{e^{c\sqrt{\log m}}} \quad . \tag{6.11}$$

By using Behrend's technique [7], this lemma has been proved in [4] and [9] for the case of $k = 3$ and arbitrary h, and in [1] for the case $h = 1$ and arbitrary k. As the proof of the above lemma simply combines the ideas of [1] and [4], we do not include it here.

Proof of Theorem 1.7, sketch. To further simplify the proof, we will use c to indicate (possibly distinct) constants that depend only on d. Let D be a fixed k-graph on d vertices, whose core L, contains a hyper-cycle R, of size r $(\leq d)$. Denote by ℓ $(\leq d)$ the size of L and assume we rename its vertices such that a copy of R is spanned by the first r vertices of L, with every vertex $1 \leq i \leq r$ playing the role of vertex i of R. As in the proof of Theorem 1.2, the main idea is to apply Lemma 4.2 by constructing a k-graph H that is ε-far from satisfying $\mathcal{P}_D$, and contains only $n^d/q(\varepsilon)$ copies of D, with $q(\varepsilon) \geq (1/\varepsilon)^{c\log 1/\varepsilon}$. To this end, we will first construct a k-graph F (as in Lemma 3.3), and then take an appropriate blow-up of it (as in Lemma 4.1).

Given ε, let m be the largest integer satisfying

$$e^{c\sqrt{\log m}} < 1/\varepsilon \quad . \tag{6.12}$$

It is easy to see that

$$m > (1/\varepsilon)^{c\log 1/\varepsilon} \quad . \tag{6.13}$$

Let Z be a $(r-k+2,c)$-linear-free subset of $[m]$. Note, that by Lemma 6.7 we have

$$|Z| \geq \frac{m}{e^{c\sqrt{\log m}}} \quad .$$

Define a k-graph F as follows: It has ℓ clusters of vertices $V_1,\ldots,V_\ell$ of size $d^{\ell+2}m$ each (thus, F has $\ell d^{\ell+2}m$ vertices). For each set of k integers $z_0,\ldots,z_{k-1} \in Z$ we put in a copy of L in F spanned by the vertices $v_1 \in V_1,\ldots,v_\ell \in V_\ell$ with v_i playing the role of i, and $v_i = E(z_0,\ldots,z_{k-1},i)$, with the function E define in (3.1) (note, that the vertices fit into the sets $V_1,\ldots,V_\ell$). As in Lemma 3.3 item (2), one can easily show that we have thus defined

$$|Z|^k \geq \frac{m^k}{e^{c\sqrt{\log m}}}$$

copies of L, with each pair sharing at most $k-1$ vertices. In particular these copies are edge disjoint. It will also be important for the rest of the proof to note that the sub-hypergraph of F, which is spanned by the first r vertices, is precisely the k-graph defined in Lemma 6.1 (with R being the hyper-cycle D in the statement of the lemma). We thus get by Corollary 6.6 that if we took an $(r-k+2,c)$-linear-free set Z, with a sufficiently small c (in terms of d), then there are $|Z|^r$ choices of vertices $v_1 \in V_1,\ldots,v_r \in V_r$ such that $v_1,\dots,v_r$ span a copy of R with v_t playing the role of vertex t or R. In what follows we call such copies of R *nice*.

Suppose we construct an n vertex k-graph H, by taking an $n/(\ell d^{\ell+2}m)$ blow-up of F (recall that F has $\ell d^{\ell+2}m$ vertices). By repeating the argument of Claim 4.4, it is not difficult to see that as F contains at least $m^k/e^{c\sqrt{\log m}}$ edge disjoint copies of L, we may infer that H contains at least $n^k/e^{c\sqrt{\log m}}$ edge-disjoint copies of L. By our choice of m in (6.12) we get that H is ε-far from being L-free. It can be easily shown that as L is the core of D, in this case H is also ε-far from being D-free.

We are thus left with showing that H contains relatively few copies of D. By repeating the argument of Claim 4.6, it can be shown that as F spans at most $|Z|^k$ nice copies of R, then H spans at most

$$|Z|^k\left(\frac{n}{\ell d^{\ell+2}m}\right)^r \le m^k\left(\frac{n}{\ell d^{\ell+2}m}\right)^r = O(n^r/m)$$

nice copies of R (observe that we always have $r>k$). Assume we prove that every copy of D spanned by H contains a nice copy of R. It would thus follow that as each copy of R is contained in at most $\binom{n}{d-r}\le n^{d-r}$ copies of D, that H spans at most $O(n^d/m)$ copies of D. By (6.13) we would get the required upper bound on the number of copies of D spanned by H.

We thus only have to show that every copy of D spanned by H contains a nice copy of R. Given a copy of D in H, consider the following homomorphism $\varphi: V(D)\to V(L)$: suppose $v\in V(D)$ is one of the vertices (in H) of the independent set that replaced vertex $i'\in V_i$, then we map v to i. Note that this is indeed a mapping from $V(D)$ to $V(L)$. Also, note that if $(i_1,\dots,i_k)\notin E(L)$ then in F there are no edges connecting vertices of $V_{i_1},\dots,V_{i_k}$. As H is a blow-up we infer that φ is indeed a homomorphism. As L is by definition a sub-hypergraph of D, the mapping φ induces a homomorphism φ', from L to itself. By the minimality of L (recall Definition 1.5), we may infer that φ' is in fact an automorphism, that is $(i_1,\dots,i_k)\in E(L)\Leftrightarrow(\varphi'(i_1),\dots,\varphi'(i_k))\in E(L)$. This means that φ' maps some copy of $R\subset D$ to the sub-hypergraph of L spanned by vertices $1,\dots,r$. Finally, by our definition of φ this means that this is a nice copy of R. □

7 Proof of Theorem 1.4

We start this section with the proof of Theorem 1.4 part (i). To this end, we need the following well known lemma of Erdős and Simonovits.

Lemma 7.1 ([10]). *For every t and k, there are constants $n_0=n_0(t,k)$, $c=c(t,k)$ and $\gamma=\gamma(t,k)>0$ with the following properties: For every $t_1,\dots,t_k\le t$, every k-graph on $n\ge n_0$ vertices, which contains $\delta(n)\cdot n^k>n^{k-\gamma}$ edges, contains at least $c\delta(n)^{t^*}n^{\bar{t}}$ copies of $K_{t_1,\dots,t_k}$, where $t^*=t_1\cdot\ldots\cdot t_k$ and $\bar{t}=t_1+\ldots+t_k$.*

We comment that the proof of this lemma is described in [10] for the case $t_1=\ldots=t_k$. However, simple modifications of the argument give the above lemma. Observe, that a k-graph, which is ε-far from being D-free, where $D=K_{t_1,\dots,t_k}$, must contain at least $\varepsilon n^k\gg n^{k-\gamma}$ edges. From the above lemma we infer that such a k-graph must contain $c\varepsilon^{t^*}n^{\bar{t}}$ copies of K. Hence, as observed in [17], there is a one-sided-error property-tester for $\mathcal{P}_D$ that simply samples $O((1/\varepsilon)^{t^*})$ sets of $\bar{t}$ vertices, and accepts iff it finds no copy of D. By the above claim it finds a copy of D with high probability. As we now show, we can improve this simple upper bound and show a lower bound, which is nearly tight in many cases.

Proof of Theorem 1.4, part (i). Let c and n_0 be the constants of Lemma 7.1. Given an input k-graph H on $n > n_0$ vertices, the algorithm samples $10\bar{t}/(c\varepsilon^{t^*/t_k})$ vertices and declares H to be D-free iff it finds no copy of D in the sub-hypergraph spanned by the set of vertices. Clearly, if H is D-free, the algorithm accepts H with probability 1. So assume H is ε-far from being D-free. We wish to show that with high probability the set of vertices spans a copy of D. Recall that such a k-graph must contain at least εn^k edges.

For a vertex v denote by $d(v)$ the degree of v, namely, the number of edges of H to which v belongs. For a vertex v in H denote by $H(v)$ the following $(k-1)$-graph: we take all the edges to which v belongs and remove v from them. Note that the number of edges of $H(v)$ is precisely $d(v)$, and that $H(v)$ obviously has at most n vertices. It follows from Lemma 7.1, that for some fixed $\gamma > 0$, if $d(v) > n^{k-1-\gamma}$, then $H(v)$ contains at least

$$c\left(\frac{d(v)}{n^{k-1}}\right)^{t^*/t_k} n^{t'}$$

copies of the $(k-1)$-partite $(k-1)$-graph $K_{t_1,\dots,t_{k-1}}$, where $t' = \bar{t} - t_k = t_1 + \ldots + t_{k-1}$. On the other hand, if $d(v) < n^{k-1-\gamma}$, then it might be the case that $H(v)$ contains no copies of $K_{t_1,\dots,t_{k-1}}$ at all. In any case, however, $H(v)$ contains at least

$$c\left(\left(\frac{d(v)}{n^{k-1}}\right)^{t^*/t_k} - \left(\frac{1}{n^{\gamma}}\right)^{t^*/t_k}\right) n^{t'} \tag{7.1}$$

copies of $K_{t_1,\dots,t_{k-1}}$. Hence, all vertices v belong to at least this many copies of the k-partite k-graph $K = K_{t_1,\dots,t_{k-1},1}$, where v plays the role of the single vertex in the last vertex class of K. Suppose we sample $\bar{t}$ vertices uniformly at random from H. Let X_v be an indicator random variable for the event that these vertices form a copy of K along with vertex v, such that v plays the role of the single vertex in the last vertex class of K. By (7.1),

$$\Pr[X_v = 1] \geq \max\left(0, c\left(\frac{d(v)}{n^{k-1}}\right)^{t^*/t_k} - c\left(\frac{1}{n^{\gamma}}\right)^{t^*/t_k}\right) \ .$$

Define $X = \sum_v X_v$. The expectation of $|X|$ thus satisfies

$$\begin{aligned} E(|X|) = \sum_v \Pr[X_v = 1] &\geq c\sum_v \left(\frac{d(v)}{n^{k-1}}\right)^{t^*/t_k} - c\sum_v n^{-\gamma t^*/t_k} \\ &\geq cn\left(\frac{\sum_v d(v)}{n^k}\right)^{t^*/t_k} - cn^{1-\gamma t^*/t_k} \geq cn(k\varepsilon)^{t^*/t_k} - o(n) \geq 2cn\varepsilon^{t^*/t_k}, \end{aligned}$$

where in the second inequality we have applied Jensen's inequality to the first summation, and in the third we have used the fact that H must contain at least εn^k edges. Observing that $|X| \leq n$, we conclude that

$$2cn\varepsilon^{t^*/t_k} \leq E(|X|) \leq cn\varepsilon^{t^*/t_k} + n \cdot \Pr[|X| \geq cn\varepsilon^{t^*/t_k}] \ .$$

Therefore,

$$\Pr[|X| \geq cn\varepsilon^{t^*/t_k}] \geq c\varepsilon^{t^*/t_k} \ .$$

Hence, by Markov's inequality, after sampling $10/c\varepsilon^{t^*/t_k}$ sets of t' vertices, with probability at least $9/10$ we find at least one set of t' vertices, which forms a copy of K with at least $cn\varepsilon^{t^*/t_k}$ of the vertices of H. After finding this set of t' vertices, all we need is t_k vertices that form a copy of K with this set of vertices, as together they would form a copy of D. By assumption, there are at least $cn\varepsilon^{t^*/t_k}$ vertices that form a copy of K with the set of t' vertices. By Markov's inequality, after sampling $10t_k/(c\varepsilon^{t^*/t_k})$ vertices, with probability at least $9/10$ we find the required set of t_k vertices. In total, we sampled $10(t_1+\ldots+t_k)/(c\varepsilon^{t^*/t_k})$ vertices, as needed. □

Proof of Theorem 1.4, part (ii). Consider the random k-graph $H(n,2k^k\varepsilon)$, that is, a k-graph on n vertices, where each set of k vertices forms an edge randomly and independently with probability $2k^k\varepsilon$. The expected number of edges in H is obviously $2k^k\varepsilon\binom{n}{k} \geq 2\varepsilon n^k$, hence, by a standard Chernoff bound, the number of edges in H is at least $\frac{3}{2}\varepsilon n^k$ with probability at least 3/4 (in fact, the probability is $1-2^{-\Theta(n^k)}$ but we do not need this stronger estimate here). As by Lemma 7.1, every k-graph with $\frac{\varepsilon}{2}n^k$ edges contains a copy of D, we get that with probability at least 3/4 H is ε-far from being D-free.

Fix a set of $d=t_1+\ldots+t_k$ vertices, where t_i is the number of vertices of D in its vertex-class number i. The number of ways to partition this set into k subsets of sizes t_i is at most $d!$. The probability that any of these partitions spans a copy of D is at most $\binom{t^*}{|E|}(2k^k\varepsilon)^{|E|}$, where $t^*=t_1\cdot\ldots\cdot t_k$. Therefore, the expected number of copies of D in $H(n,2k^k\varepsilon)$ is at most

$$\binom{n}{d}d!\binom{t^*}{|E|}2k^k\varepsilon^{|E|} \leq n^d(t^*2k^k\varepsilon)^{|E|} \ .$$

By Markov's inequality, the probability that the number of copies of D is 4 times its expectation is at most 1/4. We conclude that there is a k-graph, which is both ε-far from being D-free, and yet contains less than

$$4n^d/(1/t^*2k^k\varepsilon)^{|E|}$$

copies of D. By Lemma 4.2, the query complexity of a one-sided-error property-tester for $\mathcal{P}_D$ is $\Omega\big((1/\varepsilon)^{|E|/d}\big)$. □

8 Concluding Remarks and Open Problems

- The most interesting problem related to this paper is to give a complete characterization of the k-graphs D for which $\mathcal{P}_D$ is easily testable. We believe that the techniques presented in this paper should be useful in resolving this problem. It is known that for $k=2$, property $\mathcal{P}_D$ is easily testable iff D is bipartite. It seems likely that the "right" characterization is that for larger k, property $\mathcal{P}_D$ is easily testable iff D is k-partite. Using Theorem 1.2, we can rule out the possibility of extending the characterization of $k=2$ to, "$\mathcal{P}_D$ is easily testable iff D is 2-colorable." Indeed, note that for $k>2$, F^k, the complete k-graph on $k+1$-vertices, is 2-colorable. On the other hand, as $\mathcal{P}_{F^k}$ is equivalent to $\mathcal{P}^*_{F^k}$, we get from Theorem 1.2 that $\mathcal{P}_{F^k}$ is not easily testable.

- In light of Theorem 1.2 one may hope to show that the only k-graphs D, for which $\mathcal{P}^*_D$ is easily testable are the single k-edges. This, however, is false. As shown in [4], when $k=2$ and D is a path of length 2, property $\mathcal{P}^*_D$ has a one-sided-error tester, whose query complexity is $O(\log(1/\varepsilon)/\varepsilon)$.

It would thus be interesting to decide if for $D = D_{3,2}$ (see Theorem 1.2), the property $\mathcal{P}^*_D$ is easily testable.

- It would also be very interesting to improve the lower bounds obtained in Theorem 1.3. It should be noted that using our techniques, one cannot obtain lower bounds that match the current upper bounds. For example, the best known upper bound for testing $\mathcal{P}^*_D$, for D being a triangle, has query complexity that is a tower of exponents of height polynomial in $1/\varepsilon$. As is evident from the statement of Lemma 4.1, in order to prove a matching lower bound using our methods, one would have to use an $(3,h)$-gadget-free subset of the first m integers of size $\Omega(m/\log^* m)$ (and observe that such a set contains no 3-term arithmetic progressions). However, by a result of Bourgain [8], every subset of the first m integers of size $\Omega\big(m/\sqrt{\log m/\log\log m}\big)$ contains a 3-term arithmetic progression. Thus, the best lower bound one might hope to prove using these techniques is roughly $2^{\log(1/\varepsilon)/\varepsilon^2}$, which is very far from the current upper bound. Also, any one-sided-error property-tester for $\mathcal{P}_{K_3} = \mathcal{P}^*_{K_3}$ with query complexity $2^{O((1/\varepsilon)^2)}$ would imply an improvement of Bourgain's result.

References

[1] * N. ALON: Testing subgraphs in large graphs. *Random Structures and Algorithms*, 21:359–370, 2002. Also, Proc. 42^{nd} IEEE FOCS, IEEE (2001), 434–441. [FOCS:10.1109/SFCS.2001.959918, RSA:10.1002/rsa.10056]. 1.2, 1.3, 1.4, 6.2

[2] * N. ALON, R. A. DUKE, H. LEFMANN, V. RÖDL, AND R. YUSTER: The algorithmic aspects of the regularity lemma. *J. of Algorithms*, 16:80–109, 1994. Also, Proc. 33^{rd} IEEE FOCS, Pittsburgh, IEEE (1992), 473-481. [FOCS:10.1109/SFCS.1992.267804, JAlg:10.1006/jagm.1994.1005]. 1.2

[3] * N. ALON, E. FISCHER, M. KRIVELEVICH, AND M. SZEGEDY: Efficient testing of large graphs. *Combinatorica*, 20:451–476, 2000. Also, Proc. of 40^{th} FOCS, New York, NY, IEEE (1999), 656–666. [Combinatorica:mwapje2fdyk7ma2e]. 1.2, 4.1, 4.4, 4.7

[4] * N. ALON AND A. SHAPIRA: A characterization of easily testable induced subgraphs. In *Proc. of the* 15^{th} *Annual ACM-SIAM SODA*, pp. 935–944. ACM Press, 2004. Combinatorics, Probability and Computing, to appear. 1.2, 1.4, 1.5, 2.1, 6.2, 8

[5] * N. ALON AND A. SHAPIRA: Testing subgraphs in directed graphs. *JCSS*, 69:354–382, 2004. Also, Proc. of the 35^{th} STOC, 2003, 700–709. [STOC:780542.780644, JCSS:10.1016/j.jcss.2004.04.008]. 1.2, 1.2, 1.4

[6] * N. ALON AND A. SHAPIRA: On an extremal hypergraph problem of Brown, Erdős and Sós. Combinatorica, to appear, 2005. 1.4

[7] * F. A. BEHREND: On sets of integers which contain no three terms in arithmetic progression. *Proc. of National Academy of Sciences USA*, 32:331–332, 1946. 1.4, 6.2

[8] * J. BOURGAIN: On triples in arithmetic progression. *Geom. and Funct. Anal.*, 9:968–984, 1999. [GAFA:7wqhpp8fnnuk388g]. 8

[9] * P. ERDŐS, P. FRANKL, AND V. RÖDL: The asymptotic number of graphs not containing a fixed subgraph and a problem for hypergraphs having no exponent. *Graphs and Combin.*, 2:113–121, 1986. 2.1, 6.2

[10] * P. ERDŐS AND M. SIMONOVITS: Supersaturated graphs and hypergraphs. *Combinatorica*, 3:181–192, 1983. 7.1, 7

[11] * E. FISCHER: The art of uninformed decisions: A primer to property testing. *The Computational Complexity Column of The Bulletin of the European Association for Theoretical Computer Science*, 75:97–126, 2001. 1.1

[12] * P. FRANKL AND V. RÖDL: Extremal problems on set systems. *Random Struct. Algorithms*, 20:131–164, 2002. [RSA:10.1002/rsa.10017]. 1.2, 1.4

[13] * O. GOLDREICH, S. GOLDWASSER, AND D. RON: Property testing and its connection to learning and approximation. *JACM*, 45:653–750, 1998. Also, Proc. of 37^{th} Annual IEEE FOCS, (1996), 339–348. [FOCS:10.1109/SFCS.1996.548493, JACM:10.1145/285055.285060]. 1.1

[14] * O. GOLDREICH AND L. TREVISAN: Three theorems regarding testing graph properties. *Random Structures and Algorithms*, 23:23–57, 2003. Also, Proc. 42^{nd} IEEE FOCS, IEEE (2001), 460-469. [FOCS:10.1109/SFCS.2001.959922, RSA:10.1002/rsa.10078]. 4.1, 4.4, 4.7, 4.4

[15] * W. T. GOWERS: Hypergraph regularity and the multidimensional Szemerédi theorem. Manuscript, 2004. 1.2

[16] * I. S. GRADSHTEYN AND I. M. RYZHIK: *Tables of Integrals, Series, and Products*. Academic Press, 2000. 2.2

[17] * Y. KOHAYAKAWA, B. NAGLE, AND V. RÖDL: Efficient testing of hypergraphs. In *Proc. of* 29^{th} *ICALP*, pp. 1017–1028, 2002. [ICALP:4wa2tdcqx50avb08]. 1.2, 1.2, 1.3, 1.3, 1.4, 5.2, 7

[18] * I. LABA AND M. LACEY: On sets of integers not containing long arithmetic progressions. Manuscript, 2004. [arXiv:math/0108155]. 1.4, 2.3

[19] * B. NAGLE AND V. RÖDL: Regularity properties for triple systems. *Random Structures and Algorithms*, 23:264–332, 2003. [RSA:10.1002/rsa.10094]. 1.2

[20] * B. NAGLE, V. RÖDL, AND M. SCHACHT: The counting lemma for regular k-uniform hypegraphs. Random Structures and Algorithms, to appear. 1.2

[21] * R. A. RANKIN: Sets of integers containing not more than a given number of terms in arithmetical progression. *Proc. Roy. Soc. Edinburgh Sect. A*, 65:332–344, 1962. 1.4

[22] * V. RÖDL AND J. SKOKAN: Regularity lemma for k-uniform hypergraphs. *Random Structures and Algorithms*, 25:1–42, 2004. [RSA:10.1002/rsa.20017]. 1.2

[23] * D. RON: Property testing. *Handbook of Randomized Computing*, 2:597–649, 2001. 1.1

[24] * R. RUBINFELD AND M. SUDAN: Robust characterization of polynomials with applications to program testing. *SIAM J. on Computing*, 25:252–271, 1996. [SICOMP:10.1137/S0097539793255151]. 1.1

[25] * I. Z. RUZSA AND E. SZEMERÉDI: Triple systems with no six points carrying three triangles. In *Combinatorics (Keszthely, 1976)*, pp. 939–945. Coll. Math. Soc. J. Bolyai, 1976. 1.4

[26] * A. SHAPIRA: Behrend-type constructions for sets of linear equations. Acta Arithmetica, to appear. 1.4

[27] * E. SZEMERÉDI: Regular partitions of graphs. In *Proc. Colloque Inter. CNRS (J. C. Bermond, J. C. Fournier, M. Las Vergnas and D. Sotteau, eds.)*, pp. 399–401, 1978. 1.2

AUTHORS

Noga Alon [About the author]
professor
Schools of Mathematics and Computer Science
Tel Aviv University, Tel Aviv, Israel
nogaa@tau.ac.il
http://www.cs.tau.ac.il/~nogaa

Asaf Shapira [About the author]
PhD Candidate
School of Computer Science
Tel Aviv University, Tel Aviv, Israel
asafico@tau.ac.il
http://www.cs.tau.ac.il/~asafico

ABOUT THE AUTHORS

NOGA ALON received his Ph. D. in Mathematics at the Hebrew University of Jerusalem under the supervision of Micha Perles. He is a Baumritter Professor of Mathematics and Computer Science at Tel Aviv University, and visits frequently the Institute for Advanced Study in Princeton. He works in Combinatorics, Graph Theory and their applications to Theoretical Computer Science, focusing on combinatorial algorithms, combinatorial geometry, combinatorial number theory, algebraic and probabilistic methods in Combinatorics, and has also been working on Circuit Complexity, Streaming algorithms and topological methods in Combinatorics. He published more than three hundred and fifty research papers, and one book: The Probabilistic Method, coauthored by Joel Spencer. He is a member of the Israel National Academy of Sciences, and received the Erdős prize, the Feher prize, the Polya Prize, the Bruno Memorial Award, the Landau Prize and the Gödel Prize. Although he is not Hungarian, he likes Extremal problems, has collaborated with 28 Hungarian coauthors, his favorite function is log^*, which appears in 11 of his papers, and he is, at the moment, one of the Erdős number record holders, see Erdős number records. He is married to Nurit and has three daughters; Nilli (who has written her first paper at the age of 5), Natalie and Narkis. More details can be found at Noga Alon's Home Page.

ASAF SHAPIRA is a Ph. D. candidate at the School of Computer Science, Tel Aviv University. His main areas of research at present are property-testing and extremal problems in graph theory. He is a recipient of the Clore Foundation Ph. D. Fellowship and the IBM Ph. D. Fellowship. Thanks to his joint papers with his advisor, he holds a (perhaps by now optimal) Erdős number 2. He is also an avid traveler, skier and gourmand. More details can be found at his Home Page.