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OPTIMAL QUERY COMPLEXITY FOR RECONSTRUCTING HYPERGRAPHS

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Abstract. In this paper we consider the problem of reconstructing a hidden weighted hypergraph of constant rank using additive queries. We prove the following: Let G be a weighted hidden hypergraph of constant rank with n vertices and m hyperedges. For any m there exists a non-adaptive algorithm that finds the edges of the graph and their weights using

$$O\left(\frac{m\log n}{\log m}\right)$$

additive queries. This solves the open problem in [S. Choi, J. H. Kim. Optimal Query Complexity Bounds for Finding Graphs. *STOC*, 749–758, 2008].

When the weights of the hypergraph are integers that are less than $O(poly(n^d/m))$ where d is the rank of the hypergraph (and therefore for unweighted hypergraphs) there exists a non-adaptive algorithm that finds the edges of the graph and their weights using

$$O\left(\frac{m\log\frac{n^d}{m}}{\log m}\right).$$

additive queries.

Using the information theoretic bound the above query complexities are tight.

1. Introduction

In this paper we consider the following problem of reconstructing weighted hypergraphs of constant rank[1] (the maximal size of a hyperedge) using additive queries: Let $G = (V, E, w)$ be a weighted hidden hypergraph where $E \subset 2^V$, $|e|$ is constant for all $e \in E$, $w : E \to \mathbb{R}$, and n is the number of vertices in V. Denote by m the size of E. Suppose that the set of vertices V is known and the set of edges E is unknown. Given a set of vertices $S \subseteq V$, an additive query, $Q_G(S)$, returns the sum of weights in the sub-hypergraph induced by S. That is,

$$Q_G(S) = \sum_{e\in E\cap 2^S} w(e).$$

Our goal is to exactly reconstruct the set of edges using additive queries.

[1] Sometimes called dimension.

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	Tight Upper Bound	Adaptive Poly. time	Non-adaptive Poly. time
Loops rank= 1			
Unweighted Loops	[13, 17, 14, 6]	[8]	OPEN
Bounded Weighted Loops	[11]	OPEN	OPEN
Unbounded Weighted Loops	[10]	OPEN[†]	OPEN[§]
Graph rank= 2			
Unweighted Graph	[11]	[22]	OPEN
Bounded Weighted Graph	[11, 9]	OPEN	OPEN
Unbounded Weighted Graph	[10]	OPEN[†]	OPEN
Hypergraph rank> 2			
Unweighted HyperGraph	Ours	OPEN	OPEN
Unbounded Weighted Hypergraph	Ours	OPEN[†]	OPEN

Figure 1: Results for weighted and un-weighted hypergraphs with optimal query complexity. [†]A non-optimal adaptive query complexity algorithm for Hypergraph can be found in [12]. [§] A non-optimal non-adaptive query complexity algorithms can be found in [20] and the references within it.

One can distinguish between two types of algorithms to solve the problem. Adaptive algorithms are algorithms that take into account outcomes of previous queries while non-adaptive algorithms make all queries in advance, before any answer is known. In this paper, we consider non-adaptive algorithms for the problem. Our concern is the query complexity, that is, the number of queries needed to be asked in order to reconstruct the hypergraph.

The hypergraph reconstructing problem has known a significant progress in the past decade. For unweighted hypergraph of rank d the information theoretic lower bound gives

$$\Omega\left(\frac{m\log\frac{n^d}{m}}{\log m}\right)$$

for the query complexity for any adaptive algorithm for this problem.

Many independent results [13, 17, 14, 6][2] have proved a tight upper bound for hypergraph of rank 1, i.e., loops. A tight upper bound was proved for some subclasses of unweighted hypergraphs of rank two, i,e., graphs (Hamiltonian graphs, matching, stars and cliques etc.) [19, 18, 17, 7], unweighted graphs with $\Omega(dn)$ edges where the degree of each vertex is bounded by d [17], graphs with $\Omega(n^2)$ edges [17] and then the former was extended to d-degenerate unweighted graphs with $\Omega(dn)$ edges [19], i.e., graphs that their edges can be changed to directed edges where the out-degree of each vertex is bounded by d. A recent paper by Choi and Kim, [11], gave a tight upper bound for all unweighted graphs. In this paper we give a tight upper bound for all unweighted hypergraphs of constant rank. Our bound is tight even for weighted hypergraphs with integer weights $|w| = poly(n^d/m)$ where d is the rank of the hypergraph.

For weighted hypergraph of constant rank with unbounded weights the information theoretic lower bound gives

$$\Omega\left(\frac{m\log n}{\log m}\right)$$

[2] In [13] Djackov mentions this bound without a proof.

In [11], Choi and Kim prove a tight upper bound for loops (hypergraph of rank 1). For weighted graphs (hypergraph of rank 2) Choi and Kim, [11], proved the following: If $m > (\log n)^\alpha$ for sufficiently large α, then, there exists a non-adaptive algorithm for reconstructing a weighted graph where the weights are real numbers bounded between n^{-a} and n^b for any positive constants a and b using

$$O\left(\frac{m\log n}{\log m}\right)$$

queries.

In [9], Bshouty and Mazzawi close the gap in m and proved that for any weighted graph where the weights are bounded between n^{-a} and n^b for any positive constants a and b and *any* m there exists a non-adaptive algorithm that reconstructs the hidden graph using

$$O\left(\frac{m\log n}{\log m}\right)$$

queries. Then in [10] they extended the result to any weighted graph with any unbounded weights.

In this paper extend all the above results to any hypergraph of constant rank, i.e., the edges of the graph has constant size. This solves the open problems in [11, 9, 10].

The paper is organized as follows: In Section 2, we present notation, basic tools and some background. In Section 3, we prove the main result.

2. Preliminaries

In this section we present some background, basic tools and notation.

For an integer r let $[r]$ be the set $\{1, 2, \ldots, r\}$. For $S \subset [r]$ we define $x^S \in \{0,1\}^r$ where $x_i^S = 1$ if and only if $i \in S$. The inverse operation is $S^x = \{i \mid x_i = 1\}$. We say that $x_1, \ldots, x_d \in \{0,1\}^n$ are *pairwise disjoint* if for every $i \neq j$, we have $x_i * x_j = \mathbf{0}$ where $*$ is component-wise product of two vectors. For a prime p and integers a and b we write $a =_p b$ for $a = b \mod p$. We will also allow $p = \infty$. In this case a and b can be any real numbers and $a =_\infty b$ will mean $a = b$ as real numbers.

2.1. d-Dimensional Matrices

A *d-dimensional matrix* A of *size* $n_1 \times \cdots \times n_d$ over a field $\mathbb{F}$ is a map $A : \prod_{i=1}^d [n_i] \to \mathbb{F}$. We denote by $\mathbb{F}^{n_1\times\cdots\times n_d}$ the set of all d-dimensional matrices A of size $n_1 \times \cdots \times n_d$. We write $A_{i_1,\ldots,i_d}$ for $A(i_1, \ldots, i_d)$.

The zero map is denoted by $0^{n_1\times\cdots\times n_d}$. The matrix $B = (A_{i_1,i_2,\ldots,i_d})_{i_1\in I_1,i_2\in I_2,\ldots,i_d\in I_d}$ where $I_j \subseteq [n_j]$, is the $|I_1| \times \cdots \times |I_d|$ matrix where $B_{j_1,\ldots,j_d} = A_{\ell_1,\ldots,\ell_d}$ and ℓ_i is the j_ith smallest number in I_i. When $I_j = [n_j]$ we just write j and when $I_j = \{\ell\}$ we just write $j = \ell$. For example, $(A_{i_1,i_2,\ldots,i_d})_{i_1,i_2=\ell,i_3\in I_2,\ldots,i_d\in I_d} = (A_{i_1,i_2,\ldots,i_d})_{i_1\in[n_1],i_2\in\{\ell\},i_3\in I_2,\ldots,i_d\in I_d}$.

When $n_1 = n_2 = \cdots = n_d = n$ then we denote $\mathbb{F}^{n_1\times\cdots\times n_d}$ by $\mathbb{F}^{\times_d n}$ and $0^{n_1\times\cdots\times n_d}$ by $0^{\times_d n}$.

We say that the entry $A_{i_1,i_2,\ldots,i_d}$ is of *dimension* r if $|\{i_1, \ldots, i_d\}| = r$. For d-dimensional matrix A we denote by $wt(A)$ the number of points in $\prod_{i=1}^d [n_i]$ that are mapped to non-zero elements in $\mathbb{F}$. We denote by $wt_r(A)$ the number of points in $\prod_{i=1}^d [n_i]$ of dimension r that are mapped to non-zero elements in $\mathbb{F}$. Therefore, $wt(A) = wt_1(A) + wt_2(A) + \cdots + wt_d(A)$.

We denote by $\mathcal{A}_{d,m}$ the set of d-dimensional matrices $A \in \mathbb{F}^{\times_d n}$ where $wt_d(A) \le m$ and $\mathcal{A}^\star_{d,m}$ the set of d-dimensional matrices $A \in \mathbb{F}^{\times_d n}$ where $1 \le wt_d(A) \le m$.

For d-dimensional matrix A of size $n_1 \times \cdots \times n_d$ and $x_i \in \mathbb{F}^{n_i}$ we define

$$A(x_1,\ldots,x_d) = \sum_{i_1=1}^{n_1} \cdots \sum_{i_d=1}^{n_d} A_{i_1,i_2,\ldots,i_d} x_{1i_1} \cdots x_{di_d}.$$

The vector $v = A(\cdot, x_2, \ldots, x_d)$ is n_1-dimensional vector that its ith entry is

$$\sum_{i_2=1}^{n_2} \cdots \sum_{i_d=1}^{n_d} A_{i,i_2,\ldots,i_d} x_{2i_2} \cdots x_{di_d}.$$

For a set of d-dimensional matrices $\mathcal{B}$, a set $S \subseteq (\{0,1\}^n)^d$ is called a *zero test set* for $\mathcal{B}$ if for every $A \in \mathcal{B}$, $A \ne 0$, there is $x \in S$ such that $A(x) \ne 0$.

A d-dimensional matrix is called *symmetric* if for every $i = (i_1, \ldots, i_d) \in [n]^d$ and any permutation ϕ on $[d]$, we have $A_i = A_{\phi i}$, where $\phi i = (i_{\phi(1)}, \ldots, i_{\phi(d)})$. Notice that for a symmetric d-dimensional matrix $A \in \mathbb{F}^{\times_d n}$, $x_i \in \{0,1\}^n$ and any permutation ϕ on $[d]$, we have $A(x_1, \ldots, x_d) = A(x_{\phi(1)}, \ldots, x_{\phi(d)})$.

We will be interested mainly in the fields $\mathbb{F} = \mathbb{R}$ the field of real numbers and $\mathbb{F} = \mathbb{Z}_p$ the field of integers modulo p and in matrices of constant $d = O(1)$ dimension. Also $p > d!$. Although it seems that we are restricting the parameters, the final result has no restriction on the parameters except for $d = O(1)$. We will also abuse the notations $\mathbb{Z}_p$ and $=_p$ and allow $p = \infty$ (so in this paper ∞ is also prime number). In that case $\mathbb{Z}_\infty = \mathbb{R}$ and $=_\infty$ is equality in the filed of real numbers.

2.2. Hypergraph

A *hypergraph* G is a pair $G = (V, E)$ where $V = [n]$ is a set of elements, called nodes or vertices, and E is a set of non-empty subsets of 2^V called *hyperedges* or *edges*. The *rank* $r(G)$ of a hypergraph G is the maximum cardinality of any of the edges in the hypergraph. A hypergraph is called *d-uniform* if all of its edges are of size d.

A *weighted hypergraph* $G = (V, E, w)$ over $\mathbb{Z}_p$ is a hypergraph (V, E) with a weight function $w : E \to \mathbb{Z}_p$. For two weighted hypergraph $G_1 = (V, E_1, w_1)$ and $G_2 = (V, E_2, w_2)$ we define the weighted hypergraph $G_1 - G_2 = (V, E, w)$ where $E = \{e \in E_1 \cup E_2 \mid w_1(e) \ne w_2(e)\}$, and for every $e \in E$, $w(e) = w_1(e) - w_2(e)$. Obviously, $G_1 = G_2$ if and only if $G_1 - G_2$ is an independent set, i.e., $E = \emptyset$.

We denote by $\mathcal{G}_d$ the set of all weighted hypergraphs over $\mathbb{Z}_p$ of rank at most d, $\mathcal{G}_{d,m}$ the set of all weighted hypergraphs over $\mathbb{Z}_p$ of rank at most d and at most m edges and $\mathcal{G}^\star_{d,m}$ the set of all weighted hypergraphs over $\mathbb{Z}_p$ of rank d and at most m edges.

Let $w^\star : 2^V \to \mathbb{Z}_p$ be w extended to all possible edges where for $e \in E$, $w^\star(e) = w(e)$ and for $e \notin E$, $w^\star(e) = 0$.

An *adjacency d-dimensional matrix of a weighted hypergraph G* is a d-dimensional matrix A^G_d where $d \ge r(G)$ such that for every set $e = \{i_1, i_2, \ldots, i_\ell\}$ of size at most d we have $A^G_{d(j_1,\ldots,j_d)} =_p w^\star(e)/N(d,\ell)$ for all $j_1, \ldots, j_d$ such that $\{j_1, j_2, \ldots, j_d\} = \{i_1, \ldots, i_\ell\}$ where

$$N(d,\ell) = \sum_{i=0}^{\ell} (-1)^i \binom{\ell}{i} (\ell - i)^d.$$

That is, $N(d,\ell)$ is the number of possible sequences $(j_1,\ldots,j_d)$ such that $\{j_1,\ldots,j_d\} = \{i_1,\ldots,i_\ell\}$. Note that $N(d,\ell) \le d! < p$ and therefore $N(d,\ell) \ne_p 0$ and A_d^G is well defined.

It is easy to see that the adjacency matrix of a weighted hypergraph is a symmetric matrix and $r(G) = r$ if and only if the adjacency matrix of G has an non-zero entry of dimension r and all entries of dimension greater than r are zero.

2.3. Additive Model

In the Additive Model the goal is to exactly learn a hidden hypergraph with minimal number of additive queries. Given a set of vertices $S \subseteq V$, an *additive query*, $Q_G(S)$, returns the sum of weights in the subgraph induces by S. That is, $Q_G(S) =_p \sum_{e\in E\cap 2^S} w(e)$. Our goal is to exactly reconstruct the set of edges and find their weights using additive queries. See the many applications of this problem in [7, 11, 12].

We say that the set $\mathcal{S} = \{S_1, S_2, \cdots, S_k\} \subseteq 2^V$ is a *detecting set* for $\mathcal{G}_{d,m}$ if for any hypergraph $G \in \mathcal{G}_{d,m}$ there is S_i such that $Q_G(S_i) \ne 0$. We say that the set $\mathcal{S} = \{S_1, S_2, \cdots, S_k\} \subseteq 2^V$ is a *search set* for $\mathcal{G}_{d,m}$ if for any two distinct hypergraphs $G_1, G_2 \in \mathcal{G}_{d,m}$ there is S_i such that $Q_{G_1}(S_i) \ne Q_{G_2}(S_i)$. That is, given $(Q_G(S_i))_i$ one can uniquely determines G. We now prove the following,

Lemma 2.1. *If $\mathcal{S} = \{S_1, S_2, \cdots, S_k\} \subseteq 2^V$ is a detecting set for $\mathcal{G}_{d,2m}$ then it is a search set for $\mathcal{G}_{d,m}$.*

Proof. Let $G_1, G_2 \in \mathcal{G}_{d,m}$ be two distinct weighted hypergraphs. Let $G = G_1 - G_2$. Since $G \in \mathcal{G}_{d,2m}$ there must be $S_i \in \mathcal{S}$ such that $Q_G(S_i) \ne 0$. Since $Q_G(S_i) = Q_{G_1}(S_i) - Q_{G_2}(S_i)$ we have $Q_{G_1}(S_i) \ne Q_{G_2}(S_i)$. ■

2.4. Algebraic View of the Model

It is easy to show that for any hypergraph G of rank r the adjacency d-dimensional matrix of G, A_d^G, for $d \ge r$, is symmetric, contains a nonzero entry of dimension r and

$$Q_G(S) =_p A_d^G(x^S, x^S, \overset{d}{\ldots}, x^S) \triangleq B_d^G(x^S).$$

For a symmetric d-dimensional matrix A let $B(x) =_p A(x, x, \overset{d}{\ldots}, x)$ where $x \in \{0,1\}^n$. When $x_1, \ldots, x_d \in \{0,1\}^n$ are pairwise disjoint the following lemma shows that $A(x_1, \ldots, x_d)$ can be found by 2^d values of B.

Lemma 2.2. *If $x_1, \ldots, x_d \in \{0,1\}^n$ are pairwise disjoint then*

$$A(x_1, \ldots, x_d) =_p \frac{1}{d!} \sum_{I \in 2^{[d]}} (-1)^{d-|I|} B\left(\sum_{i\in I} x_i\right).$$

Proof. Since

$$A(x_1 + x_1', x_2, \ldots, x_d) =_p A(x_1, x_2, \ldots, x_d) + A(x_1', x_2, \ldots, x_d)$$

and

$$A(x_1, x_2, \ldots, x_d) =_p A(x_{\phi(1)}, x_{\phi(2)}, \ldots, x_{\phi(d)})$$

for any permutation ϕ on $[d]$, the result is analogous to the fact that

$$y_1y_2\cdots y_d =_p \frac{1}{d!}\sum_{I\in 2^{[d]}}(-1)^{d-|I|}\left(\sum_{i\in I} y_i\right)^d, \tag{2.1}$$

for formal variables $y_1,\ldots,y_d$. Now notice that

$$\left(\sum_{i\in I} y_i\right)^d =_p \sum_{q_1+\cdots+q_d=d}\chi\left[\{i|q_i\neq 0\}\subseteq I\right]\binom{d}{q_1\ q_2\ \cdots q_d}y_1^{q_1}\cdots y_d^{q_d},$$

where $\chi[L]=1$ if the statement L is true and 0 otherwise. Therefore, the coefficient of $y_1^{q_1}\cdots y_d^{q_d}$ in the right hand side of (2.1) is

$$\begin{aligned}&\sum_{I\in 2^{[d]}}(-1)^{d-|I|}\chi\left[\{i|q_i\neq 0\}\subseteq I\right]\binom{d}{q_1\ q_2\ \cdots q_d}\\ &=_p \binom{d}{q_1\ q_2\ \cdots q_d}\sum_{I\in 2^{[d]}}(-1)^{d-|I|}\chi\left[\{i|q_i\neq 0\}\subseteq I\right].\end{aligned}$$

Now if $\ell=|\{i|q_i\neq 0\}|<d$ then

$$\sum_{I\in 2^{[d]}}(-1)^{d-|I|}\chi\left[\{i|q_i\neq 0\}\subseteq I\right] =_p \sum_{i=\ell}^{d}(-1)^{d-i}\binom{d-\ell}{i-\ell} =_p \sum_{i=0}^{d-\ell}(-1)^{d-\ell-i}\binom{d-\ell}{i}=0.$$

If $\ell=|\{i|q_i\neq 0\}|=d$ then $q_1=q_2=\cdots=q_d=1$ and

$$\sum_{I\in 2^{[d]}}(-1)^{d-|I|}\chi\left[\{i|q_i\neq 0\}\subseteq I\right] =_p 1.$$

This implies the result. ■

Let G be a hypergraph of rank d and $G^{(i)}$, $i\le d$, be the sub-hypergraph of G that contains all the edges in G of size i then

Lemma 2.3. *If $x_1,\ldots,x_d\in\{0,1\}^n$ are pairwise disjoint then, we have that $A_d^G(x_1,\ldots,x_d)=A_d^{G^{(d)}}(x_1,\ldots,x_d)$. In particular, if $r(G)<d$ then $A_d^G(x_1,\ldots,x_d)=0$.*

Proof. Since $x_1,\ldots,x_d\in\{0,1\}^n$ are pairwise disjoint we have

$$\begin{aligned}A_d^G(x_1,\ldots,x_d) &= \sum_{i_1=1}^{n_1}\cdots\sum_{i_d=1}^{n_d}\frac{w^\star(\{i_1,i_2,\ldots,i_d\})}{N(d,|\{i_1,i_2,\ldots,i_d\}|)}x_{1i_1}\cdots x_{di_d}\\ &= \sum_{|\{i_1,\ldots,i_d\}|=d}\frac{w^\star(\{i_1,i_2,\ldots,i_d\})}{N(d,d)}x_{1i_1}\cdots x_{di_d}\\ &= A_d^{G^{(d)}}(x_1,\ldots,x_d).\end{aligned}$$

Now when $r(G)<d$ then $G^{(d)}$ is an independent set (has no edges) and $A_d^{G^{(d)}}=0$. Then $A_d^G(x)=A_d^{G^{(d)}}(x)=0$. ■

We now prove

Lemma 2.4. *Let $\Phi_d = \{z_1^{(d)}, \dots, z_{k_d}^{(d)}\} \subset (\{0,1\}^n)^d$ where for every i the vectors $z_{i,1}^{(d)}, \dots, z_{i,d}^{(d)}$ are pairwise disjoint. If Φ_d is a zero test set for $\mathcal{A}^\star_{d,(d!)m}$ then*

$$S^{\Phi_d} \triangleq \left\{ S^{y_J} \;\middle|\; y_J = \sum_{j \in J} z_{i,j}^{(d)},\ J \subset [d] \right\}$$

is a detecting set for $\mathcal{G}^\star_{d,m}$.

Proof. Let Φ_d be a zero test set for $\mathcal{A}^\star_{d,(d!)m}$. Let $G \in \mathcal{G}^\star_{d,m}$. Then $A_d^G \neq 0$ and $A_d^G \in \mathcal{A}^\star_{d,(d!)m}$. Therefore, for every $G \in \mathcal{G}^\star_{d,m}$ there is $z_i^{(d)}$ such that $A_d^G(z_i^{(d)}) \neq 0$. By Lemma 2.2,

$$A_d^G(z_i^{(d)}) =_p \frac{1}{d!} \sum_{J \in 2^{[d]}} (-1)^{d-|J|} B_d^G \left(\sum_{j \in J} z_{i,j}^{(d)} \right) \neq 0,$$

and therefore for some $J_0 \subset [d]$,

$$B_d^G \left(\sum_{j \in J_0} z_{i,j}^{(d)} \right) \neq 0,$$

which implies that $Q_G\left(S^{y_{J_0}}\right) \neq 0$ for $y_{J_0} = \sum_{j \in J_0} z_{i,j}^{(d)}$. ■

We now show

Lemma 2.5. *A detecting set for $\mathcal{G}_{d,m}$ over $\mathbb{Z}_p$ is a detecting set for $\mathcal{G}_{d,m}$ over $\mathbb{R}$.*

Proof. Consider a detecting set $\mathcal{S} = \{S_1, S_2, \cdots, S_k\} \subseteq 2^V$ for $\mathcal{G}_{d,m}$ over $\mathbb{Z}_p$. Consider a $k \times q$ matrix M where

$$q = \sum_{i=0}^{d} \binom{n}{i}$$

that its columns are labelled with sets in $2^{[n]}$ of size at most d and for every $S \subset [n]$ of size at most d we have $M[i, S] = 1$ if $S \subseteq S_i$ and 0 otherwise. Consider for every graph $G \in \mathcal{G}_{d,m}$ a q-vector v_G that its entries are labelled with subsets of $[n]$ of size at most d and $v_G[S] = w^\star(S)$. The labels in v_G are in the same order as the labels of the columns of M. Then it is easy to see that

$$Mv_G =_p (Q_G(S_1), \dots, Q_G(S_k))^T.$$

Since $Mv_G \neq_p 0$ for every $v_G \in \mathbb{Z}_p^q$ of weight at least one and at most m, every m columns in M are linearly independent over $\mathbb{Z}_p$. Since the entries of M are zeros and ones every m columns in M are linearly independent over $\mathbb{R}$. Therefore,

$$Mv_G = (Q_G(S_1), \dots, Q_G(S_k))^T \neq 0,$$

for every $v_G \in \mathbb{R}^q$ of weight at least 1 and at most m. ■

2.5. Distributions

In this subsection we give a distribution that will be used in this paper.

The *uniform disjoint distribution* $\Omega_{d,n}(x)$ over $(\{0,1\}^n)^d$ is defined as

$$\Omega_{d,n}(x) = \begin{cases} \frac{1}{(d+1)^n} & x_1, \ldots, x_d \text{ is pairwise disjoint.} \\ 0 & \text{otherwise.} \end{cases}$$

In order to choose a random vector x according to the uniform disjoint distribution, one can randomly independently uniformly choose n elements $w_1, w_2, \ldots, w_n$ where $w_i \in [d+1]$ and define the following vector $x = (x_1, x_2, \ldots, x_d) \in (\{0,1\}^n)^d$:

$$x_{ji} = \begin{cases} 1 & j = w_i \text{ and } w_i \in [d] \\ 0 & \text{otherwise.} \end{cases}$$

We call any index $k \in [n]$ such that $x_{jk} = 0$ for all $j \in [d]$ a *free index.* Let $\Gamma_{d,n} \subset (\{0,1\}^n)^d$ be the set of all pairwise disjoint d-tuple.

2.6. Preliminary Results

In this section we prove,

Lemma 2.6. *Let $A \in \mathbb{F}^{\times_d n} \backslash \{0^{\times_d n}\}$ be an adjacency d-dimensional matrix of a hypergraph G of rank d. Let $x = (x_1, x_2, \ldots, x_d) \in (\{0,1\}^n)^d$ be a randomly chosen d-tuple, that is chosen according to the distribution $\Omega_{d,n}$. Then*

$$\Pr_{x \in \Omega_{d,n}}[A(x) = 0] \le 1 - \frac{1}{(d+1)^d}.$$

Proof. Let $e = \{i_1, \ldots, i_d\}$ be an edge of size $|e| = d$ and let $x'_j = (x_{j,i_1}, \ldots, x_{j,i_d})$. Consider $\phi(x'_1, \ldots, x'_d)$ that is equal to $A(x)$ with some fixed $x_{j,i} = \xi_{j,i} \in \{0,1\}$ for $i \notin e$. Since $A(x)$ contains the monomial $M = x_{1,i_1} x_{2,i_2} \cdots x_{d,i_d}$ and no other monomial in $A(x)$ contains it, ϕ contains monomial M and therefore $\phi(x'_1, \ldots, x'_d) \not\equiv 0$. If we substitute $x_{j_1, i_{j_2}} = 0$ in ϕ for all $j_1 \neq j_2$ we still get a nonzero function $\phi'(x_{1,i_1}, x_{2,i_2}, \cdots, x_{d,i_d})$ that contains M. Therefore, there is $\xi = (\xi_{1i_1}, \xi_{2i_2}, \cdots, \xi_{di_d}) \in \{0,1\}^d$ such that $\phi'(\xi) \neq 0$. The probability that $(x_{1,i_1}, x_{2,i_2}, \cdots, x_{d,i_d}) = \xi$ and $x_{j_1, i_{j_2}} = 0$ for all $j_1 \neq j_2$ is $(1/d+1)^d$. This implies the result. ■

We will also use the following two lemmas from [9, 10].

Lemma 2.7. *Let $a \in \mathbb{Z}_p^n$ be a non-zero vector, where $p > wt(a)$ is a prime number. Then for a uniformly randomly chosen vector $x \in \{0,1\}^n$ we have*

$$\Pr_x[a^T x =_p 0] \le \frac{1}{wt(a)^\beta},$$

where $\beta = \frac{1}{2+\log 3} = 0.278943\cdots$.

Let ι be a function on non-negative integers defined as follows: $\iota(0) = 1$ and $\iota(i) = i$ for $i > 0$.

Lemma 2.8. *Let $m_1, m_2, \ldots, m_t$ be integers in $[m] \cup \{0\}$ such that $m_1 + m_2 + \cdots + m_t = \ell \ge t$. Then $\prod_{i=0}^t \iota(m_i) \ge m^{\lfloor (\ell-t)/(m-1) \rfloor}$.*

3. Reconstructing Hypergraphs

In this section we prove,

Theorem 3.1. *There is a search set for $\mathcal{G}_{d,m}$ over $\mathbb{R}$ of size $k = O\left(\frac{m\log n}{\log m}\right)$.*

Theorem 3.2. *There is a search set for $\mathcal{G}'_{d,m}$ over $\mathbb{R}$ of size $k = O\left(\frac{m\log\frac{n^d}{m}}{\log m}\right)$, where $\mathcal{G}'_{d,m}$ denotes the set of all weighted hypergraphs over $\mathbb{R}$ of rank at most d, at most m edges and weights that are integers bounded by $w = poly(n^d/m)$.*

Proof. We give the proof of Theorem 3.1. The proof of Theorem 3.2 is similar. More details in the full paper.

Let $m < p < 2m$ be a prime number. Suppose there is a zero test set from $\Gamma_{d,n}$ for $\mathcal{A}^{\star}_{d,m}$ over $\mathbb{Z}_p$ of size $T(n,m,d)$. By Lemma 2.4, there is a detecting set for $\mathcal{G}^{\star}_{d,m}$ over $\mathbb{Z}_p$ of size $2^dT(n,(d!)m,d)$. Therefore, by Lemma 2.3, there is a detecting set for $\mathcal{G}_{d,m}$ over $\mathbb{Z}_p$ of size $T'(n,m,d) = \sum_{\ell=1}^{d} 2^{\ell}T(n,(\ell!)m,\ell)$. By Lemma 2.5, there is a detecting set for $\mathcal{G}_{d,m}$ over $\mathbb{R}$ of size $T'(n,m,d)$. Finally, by Lemma 2.1, there is a search set for $\mathcal{G}_{d,m}$ over $\mathbb{R}$ of size $T'(n,2m,d)$. Now for constant d, if

$$T(n,m,d) = O\left(\frac{m\log n}{\log m}\right), \tag{3.1}$$

then $T'(n,2m,d) = O(T(n,m,d))$. Therefore it is enough to prove the following.

Lemma 3.3. *Let p be a prime number such that $m < p < 2m$. There exists a set $S = \{x_1, x_2, \ldots, x_k\} \subseteq (\{0,1\}^n)^d$ where $x_i = (x_{i,1}, \ldots, x_{i,d}) \in \Gamma_{d,n}$ for $i \in [k]$ and*

$$k = O\left(\frac{m\log n}{\log m}\right),$$

such that: for every d-dimensional matrix $A \in \mathbb{Z}_p^{\times_d n} \setminus \{0^{\times_d n}\}$ with $1 \le wt_d(A) \le m$ there exists an i such that $A(x_i) \neq_p 0$.

Proof. Since $wt_d(A) > 1$ the matrix A has at least one nonzero entry of dimension d. We will assume that all the entries of dimension less than d are zero, that is, $wt(A) = wt_d(A)$. This is because, by Lemma 2.3, the entries of dimension less than d have no effect when the vectors $x_i \in \Gamma_{d,n}$.

We divide the set of such matrices $\mathcal{A} = \{A \mid A \in \mathbb{Z}_p^{\times_d n} \setminus \{0^{\times_d n}\}$ and $wt(A) \le m\}$ into $d+1$ (non-disjoint) sets:

- $\mathcal{A}_0$: The set of all non-zero matrices $A \in \mathbb{Z}_p^{\times_d n}$ such that $wt(A) \le m/\log m$.
- $\mathcal{A}_j$ for $j = 1, \ldots, d$: The set of all non-zero matrices $A \in \mathbb{Z}_p^{\times_d n}$ such that $m \ge wt(A) > m/\log m$ and there are at least
$$\left(\frac{m}{\log m}\right)^{1/d}$$
non-zero elements in $I_j = \{i_j \mid \exists(i_1, i_2, \ldots, i_{j-1}, i_{j+1}, \ldots, i_d) : A_{i_1,i_2,\ldots,i_d} \neq 0\}$.

Note that $I = \{(i_1, i_2, \ldots, i_d) \mid A_{i_1,i_2,\ldots,i_d} \neq 0\} \subseteq I_1 \times I_2 \times \cdots \times I_d$ and therefore either $I = wt(A) \le m/\log m$ or there is j such that $|I_j| > (m/\log m)^{1/d}$. Therefore, $\mathcal{A} = \mathcal{A}_0 \cup \mathcal{A}_1 \cup \cdots \cup \mathcal{A}_d$.

Using the probabilistic method, we give $d+1$ sets of pairwise disjoint tuples of vectors $S_0, S_1, \ldots, S_d$ such that for every $j \in \{0\} \cup [d]$ and $A \in \mathcal{A}_j$ there exists a d-tuple x in S_j such that $A(x) \neq 0$ and

$$|S_0| + |S_1| + \cdots + |S_d| = O\left(\frac{m \log n}{\log m}\right).$$

Case 1: $A \in \mathcal{A}_0$: For a random d-tuple x, chosen according to the distribution $\Omega_{d,n}$ we have that

$$\Pr_x[A(x) =_p 0] \leq 1 - \frac{1}{(d+1)^d}.$$

If we randomly choose

$$k_1 = \frac{cm \log n}{\log m}$$

d-tuples, $x_1, \ldots, x_{k_1}$, according to the distribution $\Omega_{d,n}$, then the probability that $A(x_i) = 0$ for all $i \in [k_1]$ is

$$\Pr[\forall i \in [k_1] : A(x_i) =_p 0] \leq \left(1 - \frac{1}{(d+1)^d}\right)^{k_1}.$$

Therefore, by union bound, the probability that there exists a matrix $A \in \mathcal{A}_0$ such that $A(x_i) = 0$ for all $i \in [k_1]$ is

$$\begin{aligned} \Pr[\exists A \in \mathcal{A}_0, \forall i \in [k_1] : A(x_i) =_p 0] &\leq \binom{n^d}{\frac{m}{\log m}} p^{\frac{m}{\log m}} \left(1 - \frac{1}{(d+1)^d}\right)^{\frac{cm \log n}{\log m}} \\ &< n^{d\frac{m}{\log m}} n^{\frac{m}{\log m}} n^{-\frac{c'cm}{\log m}} < 1, \end{aligned}$$

for some constant c. This implies the result.

Case2: $A \in \mathcal{A}_j$ where $j = 1, \ldots, d$: We will assume w.l.o.g that $j = 1$. We first prove the following lemma

Lemma 3.4. *Let $U \subseteq \mathbb{Z}_p^{\times_{d-1} n}$ be the set of all $d-1$-dimensional matrices with weight smaller than $m^{d/(d+1)}$. For $A \in U$ let $\Upsilon(A) \subseteq [n]$ be following set*

$$\Upsilon(A) = \{j \mid \exists A_{i_1, i_2, \ldots, i_{d-1}} \neq 0 \text{ and } j \notin \{i_1, i_2, \ldots, i_{d-1}\}\}.$$

Define $Q = \{(A, j) \mid A \in U \text{ and } j \in \Upsilon(A)\}$. Then, there is a constant c_0 such that for every $C > c_0$ and

$$k_2 = C \frac{m \log n}{\log m}$$

there exists a multi-set of $d-1$-tuples of (0,1)-vectors $Z = \{z_1, z_2, \ldots, z_{k_2}\} \subseteq (\{0,1\}^n)^{d-1}$ such that for every $(A, j) \in Q$ the size of the set

$$Z_{(A,j)} = \{i \,|A(z_i) \neq 0 \text{ and } j \text{ is a free index}\}$$

is at least $\frac{k_2}{2d^d}$.

Proof. Let $z_i = (z_{i,1}, z_{i,2}, \ldots, z_{i,d-1}) \in (\{0,1\}^n)^{d-1}$ be random $d-1$-tuple of $(0,1)$-vector chosen according to the distribution $\Omega_{d-1,n}$. For $(A,j) \in Q$, and by Lemma 2.6, we have

$$\Pr_{z_i \in \Omega_{d-1,n}} [A(z_i) \neq 0 \text{ and } j \text{ is a free}] = \Pr[j \text{ is free}] \Pr[A(z_i) \neq 0 | j \text{ is free}] \geq \frac{1}{d} \cdot \frac{1}{d^{d-1}} = \frac{1}{d^d}.$$

Therefore, the expected size of $Z_{(A,j)}$ is greater than $\frac{k_2}{d^d}$. By Chernoff bound, if we randomly choose all z_i, $i \in [k_2]$ according to the distribution $\Omega_{d-1,n}$, then, we have

$$\Pr\left[|Z_{(A,j)}| \leq \frac{k_2}{2d^d}\right] \leq e^{\frac{-k_2}{8d^d}}.$$

Thus, the probability that there exists $(A,j) \in Q$ such that $|Z_{(A,j)}| \leq \frac{k_2}{2d^d}$ is

$$\begin{aligned} \Pr\left[\exists (A,j) \in Q : |Z_{(A,j)}| \leq \frac{k_2}{2d^d}\right] &\leq \frac{|Q|}{e^{\frac{-k_2}{8d^d}}} \leq \frac{|U \times [n]|}{e^{\frac{-k_2}{8d^d}}} \leq \frac{n\binom{n^{d-1}}{m^{d/(d+1)}} p^{m^{d/(d+1)}}}{e^{\frac{Cm \log n}{8d^d \log m}}} \\ &\leq \frac{n\binom{n^{d-1}}{m^{d/(d+1)}} n^{m^{d/(d+1)}}}{n^{\frac{C(\log e)m}{8d^d \log m}}} \leq \frac{n^{O\left(m^{d/(d+1)}\right)}}{n^{\frac{Cc'm}{\log m}}} < 1, \end{aligned}$$

for large enough C. This implies the result. ■

Now, Let U and Q be the sets we defined in Lemma 3.4. Let $A \in \mathcal{A}_1$. Since $wt(A) \leq m$ there are at most $m^{1/(d+1)}$ $d-1$-dimensional matrices $(A_{i_1,i_2,\ldots,i_d})_{i_1=j,i_2,\ldots,i_d}$ with weight greater than $m^{d/(d+1)}$. Therefore, there is at least

$$q = \left(\frac{m}{\log m}\right)^{1/d} - m^{1/(d+1)}$$

indices j such that $(A_{i_1,i_2,\ldots,i_d})_{i_1=j,i_2,\ldots,i_d} \in U$. Let U' contain any q indices such that $(A_{i_1,i_2,\ldots,i_d})_{i_1=j,i_2,\ldots,i_d} \in U$. Let A_U be the matrix

$$(A_{i_1,i_2,\ldots,i_d})_{i_1 \in U', i_2,\ldots,i_d}.$$

Let $z_1, z_2, \ldots, z_{k_2} \in (\{0,1\}^n)^{d-1}$ be the set we proved its existence in Lemma 3.4. We now choose $x_i \in \{0,1\}^n$, $i \in [k_2]$ in the following way: Take z_i. For every free index j, choose x_{ij} to be "1" with probability 1/2 and "0" with probability 1/2 (independently for every j). All other entries in x_i are zero, that is, all entries that correspond to non-free index j in z_i are zero. Let $u \in \{0,1\}^n$ be a vector where $u_j = 1$ if $j \in U'$ and zero otherwise. Also, for a $d-1$-tuple z_i let $v_i \in \{0,1\}^n$ be the vector where $v_{ij} = 1$ if j is a free index in z_i and $v_{ij} = 0$ otherwise. By Lemma 2.7 we have that

$$\Pr_x[A(x_i, z_i) =_p 0] \leq \prod_i \frac{1}{\iota(wt(v_i * A(\cdot, z_i)))^\beta} \leq \prod_i \frac{1}{\iota(wt(v_i * (u * A(\cdot, z_i))))^\beta}. \tag{3.2}$$

Note that, A is a hypergraph, thus, for every j such that $(A_{i_1,i_2,\ldots,i_d})_{i_1=j,i_2,\ldots,i_d} \in U$, we have that $((A_{i_1,i_2,\ldots,i_d})_{i_1=j,i_2,\ldots,i_d}, j) \in Q$. Therefore,

$$\sum_i wt(v_i * (u * A(\cdot, z_i))) \geq \frac{qk_2}{2d^d}.$$

Using Lemma 2.8 we have

$$\prod_i \iota(wt(v_i * (u * A(\cdot, z_i)))) \geq q^{\left\lfloor \frac{\frac{qk_2}{2d^d} - k_2}{q-1} \right\rfloor} = m^{c_1 k_2}.$$

Therefore, using (3.2), $\Pr_x[A(x_i, z_i) =_p 0] \le \frac{1}{m^{c_1\beta k_2}}$. Thus, the probability that there exists a matrix $A \in \mathcal{A}_1$ such that for all $i \in [k_2]$ we have $A(x_i, z_i) = 0$ is

$$\Pr_x[A(x_i, z_i) =_p 0] \le \frac{|\mathcal{A}_1|}{m^{c_1\beta k_2}} \le \frac{\binom{n^d}{m}p^m}{m^{c_1\beta k_2}} \le \frac{n^{dm}n^m}{m^{c_1\beta k_2}} < 1,$$

for large enough constant. This implies Lemma 3.3. ∎

This completes the proof of Theorem 3.1. ∎

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