Approximating Constraint Satisfaction Problems on High-Dimensional Expanders

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Abstract—We consider the problem of approximately solving constraint satisfaction problems with arity $k > 2$ ($k$-CSPs) on instances satisfying certain expansion properties, when viewed as hypergraphs. Random instances of $k$-CSPs, which are also highly expanding, are well-known to be hard to approximate using known algorithmic techniques (and are widely believed to be hard to approximate in polynomial time). However, we show that this is not necessarily the case for instances where the hypergraph is a high-dimensional expander.

We consider the spectral definition of high-dimensional expansion used by Dinur and Kaufman [FOCS 2017] to construct certain primitives related to PCPs. They measure the expansion in terms of a parameter $\gamma$ which is the analogue of the second singular value for expanding graphs. Extending the results by Barak, Raghavendra and Steurer [FOCS 2011] for 2-CSPs, we show that if an instance of MAX $k$-CSP over alphabet $[q]$ is a high-dimensional expander with parameter $\gamma$, then it is possible to approximate the maximum fraction of satisfiable constraints up to an additive error $\epsilon$ using $q^{O(1)} \cdot (k^2 \epsilon)^{O(1)}$ levels of the sum-of-squares SDP hierarchy, provided $\gamma \leq O(1) \cdot (1/(kq))^{O(1)}$.

Based on our analysis, we also suggest a notion of threshold-rank for hypergraphs, which can be used to extend the results for approximating 2-CSPs on low threshold-rank graphs. We show that if an instance of MAX $k$-CSP has threshold rank $r$ for a threshold $\tau = (1/q)^{O(1)} \cdot (1/q)^{O(1)}$, then it is possible to approximately solve the instance up to additive error $\epsilon$ using $r \cdot q^{O(1)} \cdot (k^2 \epsilon)^{O(1)}$ levels of the sum-of-squares hierarchy. As in the case of graphs, high-dimensional expanders (with sufficiently small $\gamma$) have threshold rank 1 according to our definition.

Keywords-CSP; HDX; SOS;

I. INTRODUCTION

We consider the problem of approximately solving constraint satisfaction problems (CSPs) on instances satisfying certain expansion properties. The role of expansion in understanding the approximability of CSPs with two variables in each constraint (2-CSPs) has been extensively studied and has led to several results, which can also be viewed as no-go results for PCP constructions (since PCPs are hard instances of CSPs). It was shown by Arora et al. [AKK+08] (and strengthened by Makarychev and Makarychev [MM11]) that the Unique Games problem is easily approximable on expanding instances, thus proving that the Unique Games Conjecture of Khot [Kho02] cannot be true for expanding instances. Their results were extended to all 2-CSPs and several partitioning problems in works by Barak, Raghavendra and Steurer [BRS11], Guruswami and Sinop [GS11], and Oveis Gharan and Trevisan [OGT15] under much weaker notions of expansion.

We consider the following question:

When are expanding instances of $k$-CSPs easy for $k > 2$?

At first glance, the question does not make much sense, since random instances of $k$-CSPs (which are also highly expanding) are known to be hard for various models of computation (see [KMOV17] for an excellent survey). However, while the kind of expansion exhibited by random instances of CSPs is useful for constructing codes, it is not sufficient for constructing primitives for PCPs, such as locally testable codes [BCHR05]. On the other hand, objects such as high-dimensional expanders, which possess a form of “structured multi-scale expansion” have been useful in constructing derandomized direct-product and direct-sum tests (which can be viewed as locally testable distance amplification codes) [DK17], lattices with large distance [KM18], list-decodable direct product codes [HHR+18], and are thought to be intimately connected with PCPs [DK17]. Thus, from the PCP perspective, it is more relevant to ask if this form of expansion can be used to efficiently approximate constraint satisfaction problems.

Connections to coding theory. Algorithmic results related to expanding CSPs are also relevant for the
problem of decoding locally testable codes. Consider a code $C$ constructed via $k$-local operations (such as $k$-fold direct-sum) on a base code $C_0$ with smaller distance. Then, a codeword in $C$ is simply an instance of a CSP, where each bit places a constraint on $k$ bits (which is $k$-XOR in case of direct sum) of the relevant codeword in $C_0$. The task of decoding a noisy codeword is then equivalent to finding an assignment in $C_0$, satisfying the maximum number of constraints for the above instance. Thus, algorithms for solving CSPs on expanding instances may lead to new decoding algorithms for codes obtained by applying local operations to a base code. In fact, the list decoding algorithm for direct-product codes by Dinur et al. [DHK+18] also relied on algorithmic results for expanding unique games. Since all constructions of locally testable codes need to have at least some weak expansion [DK12], it is interesting to understand what notions of expansion are amenable to algorithmic techniques.

High-dimensional expanders and our results. A $d$-dimensional expander is a downward-closed hypergraph (simplicial complex), say $X$, with $d$-edges of size at most $d + 1$, such that for every hyperedge $a \in X$ (with $|a| \leq d - 1$), a certain “neighborhood graph” $G(a)$ is a spectral expander\(^1\). Here, the graph $G(a)$ is defined to have the vertex set $\{i | a \cup \{i\} \subseteq X\}$ and edge-set $\{i, j | a \cup \{i, j\} \subseteq X\}$. If the (normalized) second singular value of each of the neighborhoods $G(a)$ is bounded by $\gamma$, $X$ is said to be a $\gamma$-high-dimensional expander ($\gamma$-HDX).

Note that (the downward closure of) a random sparse ($d + 1$)-uniform hypergraph, say with $n$ vertices and $c \cdot n$ edges, is very unlikely to be a $d$-dimensional expander. With high probability, no two hyperedges share more than one vertex and thus for any $i \in [n]$, the neighborhood graph $G_i$ is simply a disjoint union of cliques of size $d$, which is very far from an expander. While random hypergraphs do not yield high-dimensional expanders, such objects are indeed known to exist via (surprising) algebraic constructions [LSV05b, LSV05a, KO18a, CTZ18] and are known to have several interesting properties and applications [KKL16, DHK+18, KM17, KO18b, DDFH18, DK17, PRT16].

Expander graphs can simply be thought of as the one-dimensional case of the above definition. The results of Barak, Raghavendra and Steurer [BRS11] for 2-CSPs yield that if the constraint graph of a 2-CSP instance (with size $n$ and alphabet size $q$) is a sufficiently good (one dimensional) spectral expander, then one can efficiently find solutions satisfying $\text{OPT} - \epsilon$ fraction of constraints, where $\text{OPT}$ denotes the maximum fraction of constraints satisfiable by any assignment. Their algorithm is based on $(q/\epsilon)^{O(1)}$ levels of the Sum-of-Squares (SoS) SDP hierarchy, and the expansion requirement on the constraint graph is that the (normalized) second singular value should be at most $(\epsilon/q)^{O(1)}$. We show a similar result for $k$-CSPs when the corresponding simplicial complex $X_3$, which is obtained by including one hyperedge for each constraint and taking a downward closure, is a sufficiently good $(k - 1)$-dimensional expander.

Theorem I.1 (Informal). Let $\gamma$ be an instance of MAX $k$-CSP on $n$ variables taking values over an alphabet of size $q$, and let $\epsilon > 0$. Let the simplicial complex $X_3$ be a $\gamma$-HDX with $\gamma = (\epsilon/q)^{O(1)} \cdot (1/(kq))^{O(k)}$. Then, there is an algorithm based on $(k/\epsilon)^{O(1)} \cdot q^{O(k)}$ levels of the Sum-of-Squares hierarchy, which produces an assignment satisfying $\text{OPT} - \epsilon$ fraction of the constraints.

Remark I.2. While the level-$t$ relaxation for MAX $k$-CSP can be solved in time $(nq)^{O(t)}$ [RW17], the rounding algorithms used by [BRS11] and our work do not need the full power of this relaxation. Instead, they are captured by the “local rounding” framework of Guruswami and Sinop [GS12] who show how to implement a local rounding algorithm based on $t$ levels of the SoS hierarchy, in time $q^{O(1)} \cdot n^{O(t)}$ (where $q$ denotes the alphabet size).

A complete version of our results with detailed proofs is given in [AJT19].

Our techniques. We start by using essentially the same argument for analyzing the SoS hierarchy as was used by [BRS11] (specialized to the case of expanders). They viewed the SoS solution as giving a joint distribution on each pair of variables forming a constraint, and proved that for sufficiently expanding graphs, these distributions can be made close to product distributions, by conditioning on a small number of variables (which governs the number of levels required). Similarly, we consider the conditions under which joint distributions on $k$-tuples corresponding to constraints can be made close to product distributions. Since the [BRS11] argument shows how to split a joint distribution into two marginals, we can use it to recursively split a set of size $k$ into two smaller ones (one can think of all splitting operations as forming a binary tree with $k$ leaves).

However, our arguments differ in the kind of expansion required to perform the above splitting op-
erations. In the case of 2-CSPs, one splits along the edges of the constraint graph, and thus we only need the expansion of the constraint graph (which is part of the assumption). However, in the case of k-CSPs, we may split a set of size \((\ell_1 + \ell_2)\) into disjoint sets of size \(\ell_1\) and \(\ell_2\). This requires understanding the expansion of the following family of (weighted) bipartite graphs arising from the complex \(X_3\). The vertices in the graph are sets of variables of size \(\ell_1\) and \(\ell_2\) that occur in some constraint, and the weight of an edge \((a_1, a_2)\) for \(a_1 \cap a_2 = \emptyset\), is proportional to the probability that a random constraint contains \(a_1 \cup a_2\). Note that this graph may be weighted even if the k-CSP instance \(J\) is unweighted.

We view the above graphs as random walks, which we call “swap walks” on the hyperedges (faces) in the complex \(X\). While several random walks on high-dimensional expanders have been shown to have rapid mixing \([KM17]\), \([KO18b]\), \([DK17]\), \([LLP17]\), we need a stronger condition. To apply the argument from \([BRS11]\), we not only need that the second singular value is bounded away from one, but require it to be an arbitrarily small constant (as a function of \(\epsilon\), \(k\) and \(q\)). We show that this is indeed ensured by the condition that \(a_1 \cap a_2 = \emptyset\), and obtain a bound of \(O(k^{\ell_1})\cdot \gamma\) on the second singular value. This bound, which constitutes much of the technical work in the paper, is obtained by first expressing these walks in terms of more canonical walks, and then using the beautiful machinery of harmonic analysis on expanding posets by Dikstein et al. \([DDFH18]\) to understand their spectra.

The swap walks analyzed above represent natural random walks on simplicial complexes, and their properties may be of independent interest for other applications. Just as the high-dimensional expanders are viewed as “derandomized” versions of the complete complex (containing all sets of size at most \(k\)), one can view the swap walks as derandomized versions of (bipartite) Kneser graphs, which have vertex sets \(\binom{[n]}{\ell_1}\) and \(\binom{[n]}{\ell_2}\), and edges \((a, b)\) iff \(a \cap b = \emptyset\). We provide a more detailed and technical overview in Section III after discussing the relevant preliminaries in Section II.

High-dimensional threshold rank. The correlation breaking method in \([BRS11]\) can be applied as long as the graph has low threshold rank i.e., the number of singular values above a threshold \(\tau = (\epsilon/q)^{O(1)}\) is bounded. Similarly, the analysis described above can be applied, as long as all the swap walks which arise when splitting the \(k\)-tuples have bounded threshold rank. This suggests a notion of high-dimensional threshold rank for hypergraphs (discussed in Section VII), which can be defined in terms of the threshold ranks of the relevant swap walks. We remark that it is easy to show that dense hypergraphs (with \(\Omega(n^k)\) hyperedges) have small-threshold rank according to this notion, and thus it can be used to recover known algorithms for approximating k-CSPs on dense instances \([FK96]\) (as was true for threshold rank in graphs).

Other related work. While we extend the approach taken by \([BRS11]\) for 2-CSPs, somewhat different approaches were considered by Guruswami and Sinop \([GS11]\), and Oveis-Gharan and Trevisan \([OGT15]\). The work by Guruswami and Sinop relied on the expansion of the label extended graph, and used an analysis based on low-dimensional approximations of the SDP solution. Oveis-Gharan and Trevisan used low-threshold rank assumptions to obtain a regularity lemma, which was then used to approximate the CSP. For the case of k-CSPs, the Sherali-Adams hierarchy can be used to solve instances with bounded treewidth \([WJ04]\) and approximately dense instances \([YZ14]\), \([MR17]\). Brandao and Harrow \([BH13]\) also extended the results by \([BRS11]\) for 2-CSPs to the case of 2-local Hamiltonians. We show that their ideas can also be used to prove a similar extension of our results to k-local Hamiltonians on high-dimensional expanders.

In case of high-dimensional expanders, in addition to canonical walks described here, a “non-lazy” version of these walks (moving from \(s\) to \(t\) only if \(s \neq t\)) was also considered by Kaufman and Oppenheim \([KO18b]\), Anari et al. \([ALGV18]\) and Dikstein et al. \([DDFH18]\). The swap walks studied in this paper were also considered independently in a very recent work of Dikstein and Dinur \([DD19]\) (under the name “complement walks”).

In a recent follow-up work \([AJQ+19]\), the algorithms developed here were also used to obtain new unique and list decoding algorithms for direct sum and direct product codes, obtained by “lifting” a base code \(C_0\) via \(k\)-local operations to amplify distance. This work also showed that the hypergraphs obtained by considering collections of length-\(k\) walks on an expanding graph also satisfy (a slight variant of) splittability, and admit similar algorithms.

II. Preliminaries and Notation

A. Linear Algebra

Recall that for an operator \(A : V \to W\) between two finite-dimensional inner product spaces \(V\) and \(W\), the operator norm can be written as

\[
\|A\|_{\text{op}} = \sup_{f, g \neq 0} \frac{(A f, g)}{\|f\| \cdot \|g\|}.
\]
Also, for such an A the adjoint $A^\dagger : W \to V$ is defined as the (unique) operator satisfying $(Af, g) = (f, A^\dagger g)$ for all $f \in V, g \in W$. For $A : V \to W$, we take $\|A\|_{\text{op}} = \max_{\|f\|_2 = 1} \|Af\|_2$. In particular, $\|A\|_{\text{op}} = \sigma_1(A) \geq \sigma_2(A) \geq \cdots \geq \sigma_r(A)$ to be its singular values in descending order. Note that for $A : V \to V$, $\sigma_2(A)$ denotes its second largest eigenvalue in absolute value.

B. High-Dimensional Expanders

A high-dimensional expander (HDX) is a particular kind of downward-closed hypergraph (simplicial complex) satisfying an expansion requirement. We elaborate on these properties and define well known natural walks on HDXs below.

1) Simplicial Complexes:

**Definition II.1.** A simplicial complex $X$ with ground set $[n]$ is a downward-closed collection of subsets of $[n]$ i.e., for all sets $s \subseteq X$ and $t \subseteq s$, we also have $t \subseteq X$. The sets in $X$ are also referred to as faces of $X$.

We use the notation $X(i)$ to denote the collection of all faces $s$ in $X$ with $|s| = i$. When faces are of cardinality at most $d$, we also use the notation $X(\leq d)$ to denote all the faces of $X$. By convention, we take $X(0) := \{\emptyset\}$.

A simplicial complex $X(\leq d)$ is said to be a pure simplicial complex if every face of $X$ is contained in some face of size $d$. Note that in a pure simplicial complex $X(\leq d)$, the top slice $X(d)$ completely determines the complex.

Note that it is more common to associate a geometric representation to simplicial complexes, with faces of cardinality $i$ being referred to as faces of dimension $i-1$ (and the collection being denoted by $X(i)$ instead of $X(i)$). However, since we will only be treating these as hypergraphs, we prefer to index faces by their cardinality, to improve readability of related expressions.

An important simplicial complex is the complete complex.

**Definition II.2 (Complete Complex $\Delta_d(n)$).** We denote by $\Delta_d(n)$ the complete complex with faces of size at most $d$ i.e., $\Delta_d(n) := \{s \subseteq [n] \mid |s| \leq d\}$.

2) Walks and Measures on Simplicial Complexes: Let $C^k$ denote the space of real valued functions on $X(k)$ i.e.,

$$C^k := \{f \mid f : X(k) \to \mathbb{R} \} \cong \mathbb{R}^{X(k)}.$$

We describe natural walks on simplicial complexes as follows: sample a face $s' \subseteq X(i)$, according to associated measure $\Pi_k$ for all $k$, we define the inner product of functions $f,g \in C^i$, according to associated measure $\Pi_k$

$$\langle f,g \rangle = \mathbb{E}_{s \sim \Pi_k} \left[ f(s)g(s) \right] = \sum_{s \subseteq X(k)} f(s)g(s) \cdot \Pi_k(s).$$

We now define the up and down operators $U_i : C^i \to C^{i+1}$ and $D_{i+1} : C^{i+1} \to C^{i}$ as

$$[U_sg](s) = \mathbb{E}_{s' \subseteq s} \left[ g(s') \right] = \frac{1}{i + 1} \cdot \sum_{s \subseteq X} g(s \setminus \{x\})$$

$$[D_{i+1}g](s) = \mathbb{E}_{s' \supseteq s} \left[ g(s') \right],$$

$$= \frac{1}{i + 1} \cdot \sum_{s \subseteq X} g(s \cup \{x\}) \cdot \frac{\Pi_{i+1}(s \cup \{x\})}{\Pi_i(s)}.$$ An important consequence of the above definition is that $U_i$ and $D_{i+1}$ are adjoints with respect to the inner products of $C^i$ and $C^{i+1}$.

**Fact II.5.** $U_i = D_{i+1}^\dagger$, i.e., $\langle U_i f, g \rangle = \langle f, D_{i+1} g \rangle$ for every $f \in C^i$ and $g \in C^{i+1}$.

Note that the operators can be thought of as defining random walks in a simplicial complex $X(\leq d)$. The operator $U_i$ moves down from a face $s \subseteq X(i+1)$ to a face $s' \subseteq X(i)$, but lifts a function $g \in C^i$ up to a function $U_sg \in C^{i+1}$. Similarly, the operator $D_{i+1}$ can be thought of as defining a random walk which moves up
from $s \in X(i)$ to $s' \in X(i + 1)$. It is easy to verify that these walks respectively map the measure $\Pi_{i+1}$ to $\Pi$, and $\Pi$ to $\Pi_{i+1}$.

3) High-Dimensional Expansion: We recall the notion of high-dimensional expansion (defined via local spectral expansion) considered by [DK17]. We first need a few pieces of notation.

For a complex $X(\leq d)$ and $s \in X(i)$ for some $i \in [d]$, we denote by $X_s$ the link complex

$$X_s := \{ t \setminus s \mid s \subseteq t \in X \}. $$

When $|s| \leq d - 2$, we also associate a natural weighted graph $G(X_s)$ to a link $X_s$, with vertex set $X_s(1)$ and edge-set $X_s(2)$. The edge-weights are taken to be proportional to the measure $\Pi_2$ on the complex $X_s$, which is in turn proportional to the measure $\Pi_{|s|+2}$ on $X$. The graph $G(X_s)$ is referred to as the skeleton of $X_s$. Dinur and Kaufman [DK17] define high-dimensional expansion in terms of spectral expansion of the skeletons of the links.

**Definition II.6** ($\gamma$-HDX from [DK17]). A simplicial complex $X(\leq d)$ is said to be $\gamma$-High Dimensional Expander ($\gamma$-HDX) if for every $0 \leq i \leq d - 2$ and for every $s \in X(i)$, the graph $G(X_s)$ satisfies $\sigma_2(G(X_s)) \leq \gamma$, where $\sigma_2(G(X_s))$ denotes the second singular value of the (normalized) adjacency matrix of $G(X_s)$.

**C. Constraint Satisfaction Problems (CSPs)**

A $k$-CSP instance $\mathcal{I} = (H, C, w)$ with alphabet size $q$ consists of a $k$-uniform hypergraph, a set of constraints

$$C = \{ C_a \subseteq [q]^a : a \in H \},$$

and a non-negative weight function $w \in \mathbb{R}_+^H$ on the constraints, satisfying $\sum_{a \in H} w(a) = 1$.

A constraint $C_a$ is said to be satisfied by an assignment $\eta$ if we have $\eta|_a \in C_a$ i.e., the restriction of $\eta$ on $a$ is contained in $C_a$. We write, SAT$_2(\eta)$ (the weighted fraction of the constraints) satisfied by the assignment $\eta$ i.e.,

$$\text{SAT}_2(\eta) = \sum_{a \in H} w(a) \cdot 1[\eta|_a \in C_a] = \mathbb{E}_{a \sim w} \mathbf{1}[\eta|_a \in C_a].$$

We denote by OPT($\mathcal{I}$) the maximum of SAT$_2(\eta)$ over all $\eta \in [q]^V(H)$.

Any $k$-uniform hypergraph $H$ can be associated with a pure simplicial complex in a canonical way by just setting $X_3 = \{ b : \exists a \in H \text{ and } a \supseteq b \}$ – notice that $X_3(k) = H$. We will refer to this complex as the constraint complex of the instance $\mathcal{I}$. The probability distribution $\Pi_k$ on $X_3$ will be derived from the weights function $w$ of the constraint, i.e.

$$\Pi_k(a) = w(a) \quad \forall a \in X_3(k) = H.$$
the conditional covariance matrix
\[
M_{(S_1,a_1)(S_2,a_2)} = \text{Cov} \left( 1[Y_{S_1} = a_1], 1[Y_{S_2} = a_2] \right)
\]
is positive semidefinite, where \(|S_1|, |S_2| \leq (t - |T|)/2\). Here, for each pair \(S_1, S_2\) the covariance is computed using the joint distribution \(\mu_{S_1 \cup S_2}^\epsilon\). The PSD-ness be easily verified by noticing that the above matrix can be written as the Gram matrix of the vectors
\[
w((S, a), (T, b)) := \frac{1}{\|v(T, b)\|_2} \cdot \|v(T \cup S, b \alpha)\|^2 - \frac{\|v(T, b)\|^2}{\|v(T, b)\|^3} \cdot v(T, b)
\]
In this paper, we will only consider \(t\)-local ensembles such that for every conditioning on a set of size at most \(t - 2\), the conditional covariance matrix is PSD. We will refer to these as \(t\)-local PSD ensembles. We will also need a simple corollary of the above definitions.

Fact II.7. Let \((Y_1, \ldots, Y_n)\) be a \(t\)-local PSD ensemble, and let \(X\) be any simplicial complex with \(X(1) = [n]\). Then, for all \(s \leq t/2\), the collection \(\{Y_a\}_{a \subseteq X: |S| \leq s}\) is a \((t/s)\)-local PSD ensemble, where \(X(\leq s) = \bigcup_{i=1}^s X(i)\).

For random variables \(Y_S\) in a \(t\)-local PSD ensemble, we use the notation \(\{Y_S\}\) to denote the distribution of \(Y_S\) (which exists when \(|S| \leq t\)). We also define \(\text{Var}[Y_S]\) as \(\sum_{a \subseteq |g|} \text{Var}[1[Y_S = a]]\).

III. PROOF OVERVIEW: APPROXIMATING MAX 4-XOR

We consider a simple example of a specific k-CSP, which captures most of the key ideas in our proof. Let \(J\) be an unweighted instance of 4-XOR on \(n\) Boolean variables. Let \(H\) be a 4-uniform hypergraph on vertex set \([n]\), with a hyperedge corresponding to each constraint i.e., each \(a = \{i_1, i_2, i_3, i_4\} \in H\) corresponds to a constraint in \(J\) of the form
\[
x_{i_1} + x_{i_2} + x_{i_3} + x_{i_4} = b_a \quad \text{(mod 2),}
\]
for some \(b_a \in \{0, 1\}\). Let \(X\) denote the constraint complex for the instance \(J\) such that \(X(1) = [n]\), \(X(4) = H\) and let \(\Pi_1, \ldots, \Pi_4\) be the associated distributions (with \(\Pi_4\) being uniform on \(H\)).

Local vs global correlation: the BRS strategy. We first recall the strategy used by [BRS11], which also suggests a natural first step for our proof. Given a 2-CSP instance with an associated graph \(G\), and a \(t\)-local PSD ensemble \(Y_1, \ldots, Y_n\) obtained from the SoS relaxation, they consider if the “local correlation” of the ensemble is small across the edges of \(G\) (which correspond to constraints) i.e.,
\[
\mathbb{E} \sum_{\{i,j\} \sim G} \left\| \{Y_i, Y_j\} - \{Y_i\} \{Y_j\} \right\|_1 \leq \epsilon.
\]
If the local correlation is indeed small, we easily produce an assignment achieving a value \(\text{SDP} - \epsilon\) in expectation, simply by rounding each variable \(x_i\) independently according to the distribution \(\{Y_i\}\). On the other hand, if this is not satisfied, they show (as a special case of their proof) that if \(G\) is an expander with second eigenvalue \(\lambda \leq c \cdot (q^2/q^2)\), then variables also have a high “global correlation”, between a typical pair \((i, j) \in [n]^2\). Here, \(q\) is the alphabet size and \(c\) is a fixed constant. They use this to show that for \(Y_1, \ldots, Y_n\) obtained by conditioning on the value of a randomly chosen \(Y_{i_0}\), we have
\[
\mathbb{E} \left[ \text{Var}[Y_{i_0}] \right] - \mathbb{E} \sum_{i \neq i_0} \mathbb{E} \left[ \text{Var}[Y_i] \right] \geq \Omega(\epsilon^2/q^2),
\]
where the expectations over \(i\) and \(i_0\) are both according to the stationary distribution on the vertices of \(G\). Since the variance is bounded between 0 and 1, this essentially shows that the local correlation must be at most \(\epsilon\) after conditioning on a set of size \(O(q^2/q^2)\) (although the actual argument requires a bit more care and needs to condition on a somewhat larger set).

Extension to 4-XOR. As in [BRS11], we check if the \(t\)-local PSD ensemble \((Y_1, \ldots, Y_n)\) obtained from the SDP solution satisfies
\[
\mathbb{E} \left[ \text{Var}[Y_{i_1} Y_{i_2} Y_{i_3} Y_{i_4}] - \{Y_{i_1}\} \{Y_{i_2}\} \{Y_{i_3}\} \{Y_{i_4}\} \right]_1 \leq \epsilon.
\]
As before, independently sampling each \(x_i\) from \(Y_i\) gives an expected value at least \(\text{SDP} - \epsilon\) in this case. If the above inequality is not satisfied, an application of triangle inequality gives
\[
\mathbb{E} \sum_{\{i_1, i_2, i_3, i_4\} \in H} \left( \left\| \{Y_{i_1} Y_{i_2} Y_{i_3} Y_{i_4}\} - \{Y_{i_1}\} \{Y_{i_2}\} \{Y_{i_3}\} \{Y_{i_4}\} \right\|_1 + \right) > \epsilon.
\]
Symmetrizing over all orderings of \(i_1, i_2, i_3, i_4\), we can write the above as
\[
\epsilon_2 + 2 \cdot \epsilon_1 > \epsilon,
\]
which gives \(\max \{\epsilon_1, \epsilon_2\} \geq \epsilon/3\). Here,
\[
\epsilon_1 := \mathbb{E} \sum_{\{i,j\} \sim J} \left\| \{Y_i, Y_j\} - \{Y_i\} \{Y_j\} \right\|_1, \quad \text{and}
\epsilon_2 := \mathbb{E} \sum_{\{i,j,k,l\} \sim J} \left\| \{Y_i Y_j Y_k Y_l\} - \{Y_i\} \{Y_j\} \{Y_k\} \{Y_l\} \right\|_1 = \mathbb{E} \sum_{\{i,j,k,l\} \sim J} \left\| \{Y_{\{i,j\}} Y_{\{k,l\}}\} - \{Y_{\{i,j\}}\} \{Y_{\{k,l\}}\} \right\|_1.
\]
As before, \(\epsilon_1\) measures the local correlation across edges of a weighted graph \(G_1\) with vertex set \(X(1) = [n]\) and edge-weights given by \(\Pi_2\). Also, \(\epsilon_2\) measures the analogous quantity for a graph \(G_2\) with vertex set \(X(2)\) (pairs of variables occurring in constraints) and edge-weights given by \(\Pi_4\).
Recall that the result from [BRS11] can be applied to any graph $G$ over variables in a 2-local PSD ensemble, as long as the $c_2(G)$ is small. Since $\{Y_i\}_{i \in [n]}$ and $\{Y_s\}_{s \in X(2)}$ are both $(t/2)$-local PSD ensembles (by Fact II.7), we will apply the result to the graph $G_1$ on the first ensemble and $G_2$ on the second ensemble. We consider the potential

$$\Phi(Y_1, \ldots, Y_n) := \mathbb{E}_{i \sim \Pi_1} \text{Var}[Y_i] + \mathbb{E}_{s \sim \Pi_2} \text{Var}[Y_s].$$

Since local correlation is large along at least one of the graphs $G_1$ and $G_2$, using the above arguments (and the non-decreasing nature of variance under conditioning) it is easy to show that in expectation over the choice of $\{i_0, j_0\} \sim \Pi_2$ and $\beta \in [\gamma]^2$ chosen from $\{Y_{i_0, j_0}\}$, the conditional ensemble $(Y_1', \ldots, Y_n')$ satisfies

$$\Phi(Y_1', \ldots, Y_n') - \mathbb{E}_{i_0, j_0} \Phi(Y_1', \ldots, Y_n') = \Omega(c^2),$$

provided $G_1$ and $G_2$ satisfy $c_2(G_1), c_2(G_2) \leq c \cdot 2^2$ for an appropriate constant $c$.

The bound on the eigenvalue of $G_1$ follows simply from the fact that it is the skeleton of $X$, which is a $\gamma$-HDG. Obtaining bounds on the eigenvalues of $G_2$ and similar higher-order graphs, constitutes much of the technical part of this paper. Note that for a random sparse instance of MAX 4-XOR, the graph $G_2$ will be a matching with high probability (since $\{i_1, i_2\}$ in a constraint will only be connected to $\{i_3, i_4\}$ in the same constraint). However, we show that in case of a $\gamma$-HDG, this graph has second eigenvalue $O(\gamma)$. We analyze these graphs in terms of modified high-dimensional random walks, which we call “swap walks”.

We remark that our potential and choice of a “seed set” of variables to condition on, is slightly different from [BRS11]. To decrease the potential function above, we need that for each level $X(i)$ ($i = 1, 2$ in the example above) the seed set must contain sufficiently many independent samples from $X(i)$ sampled according to $\Pi_i$. This can be ensured by drawing independent samples from the top level $X(k)$ (though $X(2)$ suffices in the above example). In contrast, the seed set in [BRS11] consists of random samples from $\Pi_1$. The graph $G_2$ defined above can be thought of as a random walk on $X(2)$, which starts at a face $s \in X(2)$, moves up to a face (constraint) $s' \in X(4)$ containing it, and then descends to a face $t \in X(2)$ such that $t \subset s'$ and $s \cap t = \emptyset$ i.e., the walk “swaps out” the elements in $s$ for other elements in $s'$. Several walks considered on simplicial complexes allow for the possibility of a non-trivial intersection, and hence have second eigenvalue lower bounded by a constant. On the other hand, swap walks completely avoid any laziness and thus turn out to have eigenvalues which can be made arbitrarily small. To understand the eigenvalues for this walk, we will express it in terms of other canonical walks defined on simplicial complexes.

Recall that the up and down operators can be used to define random walks on simplicial complexes. The up operator $U_1 : C^i \rightarrow C^{i+1}$ defines a walk that moves down from a face $s \in X(i+1)$ to a random face $t \in X(i), t \subset s$ (the operator thus “lifts” a function in $C_i$ to a function in $C_{i+1}$). Similarly, the down operator $D_1 : C^i \rightarrow C^{i-1}$ moves up from a face $s \in X(i-1)$ to $t \in X(i), t \supset s$, with probability $\Pi_i(t) / (i \cdot \Pi_{i-1}(s))$. These can be used to define a canonical random walk $N_{2,2}^{(u)} := D_3 \cdots D_{u+2} U_{u+1} \cdots U_2$, $N_{2,2}^{(d)} : C^2 \rightarrow C^2$, which moves from up for $u$ steps $s \in X(2)$ to $s'$, and then descends back to $t \in X(2)$. Such walks were analyzed optimally by Dinur and Kaufman [DK17], who proved that $\lambda_2(N_{2,2}^{(u)}) = 2/(u+2) + O_u(\gamma)$ when $X$ is a $\gamma$-HDG. Thus, while this walk gives an expanding graph with vertex set $X(2)$, the second eigenvalue cannot be made arbitrarily small for a fixed $u$ (recall that we are interested in showing that $c_2(G_2) \leq c \cdot 2^2$). However, note that we are only interested in $N_{2,2}^{(u)}$ conditioned on the event that the two elements from $s$ are “swapped out” with new elements in the final set $T$ i.e., $s \cap T = \emptyset$. We define $S_{2,2}^{(u)}(s, t) := \begin{cases} \frac{1}{(u+2)} \cdot N_{2,2}^{(u)} & \text{if } |t \setminus s| = j, \\ 0 & \text{otherwise} \end{cases}$

where the normalization is to ensure stochasticity of the matrix. In this notation, the graph $G_2$ corresponds to the random-walk matrix $S_{2,2}^{(2,2)}$. We show that while $c_2(N_{2,2}^{(2)}) \approx 1/2$, we have that $c_2(S_{2,2}^{(2,2)}) = O(\gamma)$. We first write the canonical walks in terms of the swap walks. Note that $N_{2,2}^{(2)} = \frac{1}{6} \cdot 1 + \frac{2}{3} \cdot S_{2,2}^{(2,1)} + \frac{1}{6} \cdot S_{2,2}^{(2,2)}$, since the “descent” step from $s' \in X(4)$ containing $s \in X(2)$, produces a $t \in X(2)$ which “swaps out” 0,1 and 2 elements with probabilities $1/6, 2/3$ and $1/6$ respectively. Similarly,$N_{2,2}^{(1)} = \frac{1}{3} \cdot 1 + \frac{2}{3} \cdot S_{2,2}^{(1,1)}.$

Finally, we use the fact (proved in Section IV) that while the canonical walks do depend on the “height” $u$ (i.e., $N_{2,2}^{(u)} \neq N_{2,2}^{(u')}$) the swap walks (for a fixed number
of swaps $j$) are independent of the height to which they ascend! In particular, we have

$$S_{2,2}^{(2,1)} = S_{2,2}^{(1,1)}.$$  

Using these, we can derive an expression for the swap walk $S_{2,2}^{(2,2)}$ as

$$S_{2,2}^{(2,2)} = 1 + 6 \cdot N_{2,2}^{(2)} - 6 \cdot N_{2,2}^{(1)} = 1 + 6 \cdot (D_3 D_4 U_2 - D_3 U_2)$$

To understand the spectrum of operators such as the ones given by the above expression, we use the beautiful machinery for harmonic analysis over HDXs (and more generally over expanding posets) developed by Dikstein et al. [DDFH18]. They show how to decompose the spaces $C^k$ into approximate eigenfunctions for operators of the form $DU$. Using these decompositions and the properties of expanding posets, we can show that distinct eigenvalues of the above operator are approximately the same (up to $O(\gamma)$ errors) when analyzing the walks on the complete complex. Finally, we use the fact that swap walks in a complete complex correspond to Kneser graphs (for which the eigenvectors and eigenvalues are well-known) to show that $\lambda_2(S_{2,2}^{(2,2)}) = O(\gamma)$.

**Splittable CSPs and high-dimensional threshold rank.** We note that the ideas used above can be generalized (at least) in two ways. In the analysis of distance from product distribution for a 4-tuple of random variables forming a contraint, we split it in 2-tuples. In general, we can choose to split tuples in a $k$-CSP instance along any binary tree $T$ with $k$ leaves, with each parent node corresponding to a swap walk between tuples forming its children. Finally, the analysis from [BRS11] also works if the each of the swap walks in some $T$ have a bounded number (say $r$) of eigenvalues above some threshold $\tau$, which provide a notion of high-dimensional threshold rank for hypergraphs. We refer to such an instance as a $(T, \tau, r)$-splittable.

The arguments sketched above show that high-dimensional expanders are $(T, O(\gamma), 1)$-splittable for all $T$. Since the knowledge of $T$ is only required in our analysis and not in the algorithm, we say that $\text{rank}_T(3) \leq r$ (or that $T$ is $(\tau, r)$-splittable) if $T$ is $(T, \tau, r)$-splittable for any $T$. We defer the precise statement of results for $(\tau, r)$-splittable instances to Section VII.

**IV. Walks**

It is important to note that both $U_i$ and $D_{i+1}$ are row-stochastic matrices, i.e. we can think of them as the probability matrices describing the movement of a walk from $X(i+1)$ to $X(i)$; and from $X(i)$ to $X(i+1)$ respectively.

Concretely, we will think $[D_{i+1}^\top e_s]_t(t)$ as the probability of the walk moving up from $s \in X(i)$ to $t \in X(i+1)$. Similarly, we will think of $[U_i^\top e_t]_s(s)$ as the walk moving down from $t \in X(i+1)$ to $s \in X(i)$.

By referring to the definition of the up and down operators in Section II, we observe

$$[D_{i+1}^\top e_s]_t(t) = \frac{1}{t+1} \frac{\Pi_{i+1}(t) \Pi_i(s)}{\Pi_i(s)}$$

With this observation it is easy to see that our notion of random walk respects the probability distributions $\Pi_j$, i.e. we have

$$U_i^\top \Pi_{i+1} = \Pi_i \quad \text{and} \quad D_{i+1}^\top \Pi_i = \Pi_{i+1},$$

i.e., randomly moving up from a sample of $\Pi_j$ gives a sample of $\Pi_{j+1}$ and similarly, moving down from a sample of $\Pi_{j+1}$ results in a sample of $\Pi_j$.

Instead of going up and down by one dimension, one can try going up or down by multiple dimensions since $(D_{i+1} \cdots D_{i+\ell})$ and $(U_i \cdots U_j)$ are still row-stochastic matrices. Further, the corresponding probability vectors still have intuitive explanations in terms of the distributions $\Pi_j$. For a face $s \in X(k)$, we introduce the notation

$$p_s^{(u)} = (D_{k+1} \cdots D_{k+u})^\top e_s$$

where we take $p_s^{(0)} = e_s$. This notation will be used to denote the probability distribution of the up-walk starting from $s \in X(k)$ and ending in a random face $t \in X(k+u)$ satisfying $t \supseteq s$.

Note that the following Lemma together with Proposition II.4 implies that $p_s^{(u)}$ is indeed a probability distribution.

**Proposition IV.1.** For $s \in X(k)$ and $a \in X(k+u)$ one has,

$$p_s^{(u)}(a) = 1[a \supseteq s] \cdot \frac{1}{(k+u)^{\Pi_k(a)}} \frac{\Pi_{k+u}(a)}{\Pi_k(s)}.$$  

Similarly, we introduce the notation $q_a^{(u)}$, as

$$q_a^{(u)}(s) = (U_{k+u-1} \cdots U_k)^\top e_s,$$

i.e. for the probability distribution of the down-walk starting from $a \in X(k+u)$ and ending in a random face of $X(k)$ contained in $a$. The following can be verified using Proposition IV.1, and the fact that $(U_{k+u-1} \cdots U_k)^\top = D_{k+u} \cdots D_{k+1}$. 


Corollary IV.2. Let $X(\leq d)$ be a simplicial complex, and $k,u \geq 0$ be parameters satisfying $k+u \leq d$. For $s \in X(k+u)$ and $s' \in X(k)$, one has
\[ q_s^{(u)}(s) = \frac{1}{k+u} \cdot 1[s \leq s]. \]

In the remainder of this section, we will try to construct more intricate walks on $X$ from $X(k)$ to $X(l)$.

A. The Canonical and the Swap Walks on a Simplicial Complex

Definition IV.3 (Canonical and Swap $u$-Walks). Let $d \geq 0$, $X(\leq d)$ be a simplicial complex, and $k,l,u \geq 0$ be parameters satisfying $l \leq k, u \leq l$ and $d \geq k+u$, where the constraints on these parameters are to ensure well-definedness. We will define the following random walks,

- **canonical $u$-walk** from $X(k)$ to $X(l)$. Let $N_{k,l}^{(u)}$ be the (row-stochastic) Markov operator that represents the following random walk: Starting from a face $s \in X(k)$,
  - (random ascent/up-walk) randomly move up a face $s'' \in X(k+u)$ that contains $s$, where $s''$ is picked with probability
    \[ p_s^{(u)}(s'') = \frac{1}{k+u} \cdot 1[s'' \subseteq s]. \]
  - (random descent/down-walk) go to a face $s' \in X(l)$ picked uniformly among all the $l$-dimensional faces that are contained in $s''$, i.e., the set $s'$ is picked with probability
    \[ q_{s''}(s') = \frac{1[s' \subseteq s']}{{k+u\choose l}} = [(U_{k+u-1} \cdots U_l)\trans e_{s'}](s''). \]

The operator $N_{k,l}^{(u)} : C^l \to C^k$ satisfies the following equation,
\[ N_{k,l}^{(u)} = D_{k+1} \cdots D_{k+u} U_{k+u-1} \cdots U_k. \]
Notice that we have $N_{k,k}^{(0)} = I$ and $N_{k,l}^{(0)} = (U_{k-1} \cdots U_l)$ for $l < k$.

- **swapping walk** from $X(k)$ to $X(l)$. Let $S_{k,l}$ be the Markov operator that represents the following random walk: Starting from a face $s \in X(k)$,
  - (random ascent/up-walk) randomly move up to a face $s'' \in X(k+u)$ that contains $s$, where as before $s''$ is picked with probability
    \[ p_s^{(l)}(s'') = \frac{1}{k+u} \cdot 1[s'' \subseteq s]. \]
  - (deterministic descent) deterministically go to $s' = s''\cap s \in X(l)$.

For our applications, we will need to show that the walk $S_{k,l}$ has good spectral expansion whenever $X$ is a $d$-dimensional $\gamma$-expander, for $\gamma$ sufficiently small. To show this, we will relate the swapping walk operator $S_{k,l}$ on $X$ to the canonical random walk operators $N_{k,l}^{(u)}$ (q.v. Lemma IV.4).

By the machinery of expanding posets (q.v. Section V) it is possible to argue that the spectral expansion of the random walk operator $N_{k,l}^{(u)}$ on a high dimensional expander will be close to that of the complete complex. This will allow us to conclude using the relation between the swapping walks and the canonical walks (q.v. Lemma IV.4) that the spectral expansion of the swapping walk on $X$, will be comparable with the spectral expansion of the swap walk on the complete complex. More precisely, we will show

Lemma IV.4 (Lemma V.34). For any $d,k,l \geq 0$, and the complete simplicial complex $X(\leq d)$, one has the following: If $k \geq l \geq 0$ and $d \geq k + l$, we have
\[ \sigma_2(S_{k,l}) = O_{k,l}(\gamma) \]
where $S_{k,l}$ is the swapping walk on $X$ from $X(k)$ to $X(l)$.

To prove Theorem IV.5 we will need to define an intermediate random walk that we will call the $j$-swapping $u$-walk from $X(k)$ to $X(l)$:

Definition IV.6 ($j$-swapping $u$-walk from $X(k)$ to $X(l)$). Given $d,u,j,k,l \geq 0$ satisfying $l \leq k, j \leq u, u \leq l$, and $d \geq k + u$. Let $S_{k,l}^{(u)}$ be the Markov operator that represents the following random walk from $X(k)$ to $X(l)$ on a $d$-dimensional simplicial complex $X$: Starting from $s \in X(k)$

- (random ascent/up-walk) randomly move up to a face $s'' \in X(k+u)$ that contains $s$, where $s''$ is picked with probability
  \[ p_s^{(u)}(s'') = \frac{1}{k+u} \cdot 1[s'' \subseteq s]. \]
- (conditioned descent) go to a face $s' \in X(l)$ sampled uniformly among all the subsets of $s'' \in X(k+u)$ that have intersection $j$ with $s'' \cap s$, i.e., $|s' \cap (s'' \cap s)| = j$.

Notice that $S_{k,l} = S_{k,l}^{(0)}$ for any $k$ and $l = S_{k,k}^{(u)}$ for any $u$.

Remark IV.7. We will prove that the parameter $u$ does not effect the swapping walk $S_{k,l}^{(u)}$ so long as $u \geq j$, i.e. for all $u, u' \geq j$ we have $S_{k,l}^{(u)} = S_{k,l}^{(u')}$. Thus, we will often write $S_{k,l}^{(j)}$ for $S_{k,l}^{(j)}$.
B. Swap Walks Are Height Independent

Recall that the swap walk $S_{k,l}^{(u,j)}$ is the conditional walk defined in terms of $N_{k,l}^{(u)}$ where $s \in X(k)$ is connected to $t \in X(l)$ only if $|t \setminus s| = j$. The parameter $u$ is called the height of the walk, namely the number of times it moves up. Since up and down operators have second singular value bounded away from 1, the second singular value of $N_{k,l}^{(u)}$ shrinks as $u$ increases. In other words, the operator $N_{k,l}^{(u)}$ depends on the height $u$. Surprisingly, the walk $S_{k,l}^{(u,j)}$, which is defined in terms of $N_{k,l}^{(u)}$, does not depend on the particular choice of $u$ as long as it is well defined. More precisely, we have the following result.

Lemma IV.8. If $X$ is a $d$-dimensional simplicial complex, $0 \leq l \leq k$, and $u, u' \in [j, d - k]$, then

$$S_{k,l}^{(u,j)} = S_{k,l}^{(u',j)}.$$  

In order to obtain Lemma IV.8, we will need a simple proposition:

Proposition IV.9. Let $s \in X(k), s' \subseteq s$ and $|t'| = j$. Suppose $s' \sqcup t' \in X(l)$. Then, we have

$$S_{k,l}^{(u,j)}(s, s' \sqcup t') = \frac{1}{\binom{k-l}{j} \cdot \binom{u}{j}} \cdot \sum_{a \in X(k+l) \setminus X(l)} p_s^{(u)}(a).$$

Lemma IV.10 (Height Independence). Let $u \in [j, d - k]$. For any $s \in X(k), s' \subseteq s$ and $t' \in X(l)$ satisfying $s' \sqcup t' \in X(l)$, we have the following,

$$S_{k,l}^{(u,j)}(s, s' \sqcup t') = \frac{1}{\binom{k-l}{j} \cdot \binom{k+j+l}{j}} \cdot \frac{\Pi_{k+j}(s \sqcup t')} {\Pi_k(s)}.$$

In particular, the choice of $u \in [j, d - k]$ does not affect the swap walk.

Since the choice of $u$ does not affect the formula, we obtain Lemma IV.8.

C. Canonical Walks in Terms of the Swap Walks

We show that the canonical walks are given by an average of swap walks with respect to the hypergeometric distribution.

Lemma IV.11. Let $u, l, k, d \geq 0$ be given satisfying $l \leq k$ and $u \leq l$. Then, we have the following formula for the canonical $u$-walk on any $X(\leq d)$ satisfying $d \geq k + u$

$$N_{k,l}^{(u)} = \sum_{j=0}^{u} \binom{u}{j} \binom{l-j}{u-j} \cdot S_{k,l}^{(j)}.$$  

D. Inversion: Swap Walks in Terms of Canonical Walks

We show how the swap walks can be obtained as a signed sum of canonical walks. This result follows from binomial inversion which we recall next.

Fact IV.12 (Binomial Inversion, [BS02]). Let $(a_n)_{n \geq 0}, (b_n)_{n \geq 0}$ be arbitrary sequences. Suppose for all $n \geq 0$ we have,

$$b_n = \sum_{j=0}^{n} \binom{n}{j} \cdot (-1)^{j} \cdot a_j.$$

Then, we also have

$$a_n = \sum_{j=0}^{n} \binom{n}{j} \cdot (-1)^{j} \cdot b_j.$$

Corollary IV.13. Let $k, l, d \geq 0$ be given parameters such that $k + 1 \leq d$ and $k \geq 1$. For any simplicial complex $X(\leq d)$, one has the following formula for the $u$-swapping walk from $X(k)$ to $X(l)$ in terms of the canonical $j$-walks:

$$\left(\begin{array}{c} k \\ l - u \end{array}\right)S_{k,l}^{(u)} = \sum_{j=0}^{u} (-1)^u \cdot \binom{k+j}{l-j} \cdot \binom{u}{j} \cdot N_{k,l}^{(j)}.$$  

V. Spectral Analysis of Swap Walks

Swap walks arise naturally in our $k$-CSP approximation scheme on HDXs where the running time and the quality of approximation depend on the expansion of these walks. For this reason, we analyze the spectra of swap walks. We show that swap walks $S_{k,l}$ of $\gamma$-HDXs are indeed expanding for $\gamma$ sufficiently small. More precisely, the first main result of this section is the following.

Theorem V.1 (Swap Walk Spectral Bound). Let $X(\leq d)$ be a $\gamma$-HDX with $d \geq 2k$. Then the second largest singular value $\sigma_2(S_{k,l})$ of the swap operator $S_{k,l}$ is

$$\sigma_2(S_{k,l}) \leq \gamma \cdot \left(2^{d-k} \cdot k^2 \cdot 2^{3k} \cdot k^k\right).$$

Theorem V.1 is enough for the analysis of our $k$-CSP approximation scheme when $k$ is a power of two. However, to analyze general $k$-CSPs on HDXs we need to understand the spectra of general swap walks $S_{k,l}$ where $k$ may differ from $l$. Therefore, we generalize the spectral analysis of $S_{k,l}$ above to $S_{k,l}$ obtaining Theorem V.2, our second main result of this section.

Theorem V.2 (Rectangular Swap Walk Spectral Bound). Suppose $X(\leq d)$ is a $\gamma$-HDX with $d \geq k + l$ and $k \leq l$. Then the largest non-trivial singular value $\sigma_2(S_{k,l})$ of the swap operator $S_{k,l}$ is

$$\sigma_2(S_{k,l}) \leq \sqrt{\gamma \cdot \left(2^d \cdot k^2 \ell^2 \cdot 2^{3k} \cdot 4^l \cdot k^k\right)}.$$  

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A. Square Swap Walks $S_{k,k}$

We prove Theorem V.1 by connecting the spectral structure of $S_{k,k}$ of general $\gamma$-HDXs to the well behaved case of complete simplicial complexes. To distinguish these two cases we denote by $S_{k,k}^\Delta$ the swap $S_{k,k}$ of complete complexes. In fact, $S_{k,k}^\Delta$ is the random walk operator of the well known Kneser graph $K(n,k)$ (see Definition V.3).

Definition V.3 (Kneser Graph $K(n,k)$ [GM15]). The Kneser graph $K(n,k)$ is the graph $G = (V,E)$ where $V = \binom{[n]}{k}$ and $E = \{\{s,t\} \mid s \cap t = \emptyset\}$.

Then at least for complete complexes we know that $S_{k,k}^\Delta$ is expanding. This is a direct consequence of Fact V.4.

Fact V.4 (Kneser Graph [GM15]). The singular values of the Kneser graph $K(n,k)$ are

$$\sigma_2(S_{k,k}^\Delta) = O_k(1/n)$$

for $i = 0, \ldots, k$.

This means that $\sigma_2(S_{k,k}^\Delta) = O_k(1/n)$ as shown in Claim V.5.

Claim V.5. Let $d \geq 2k$ and $\Delta_d(n)$ be the complete complex. The second largest singular value $\sigma_2(S_{k,k}^\Delta)$ of the swap operator $S_{k,k}^\Delta$ on $\Delta_d(n)$ is

$$\sigma_2(S_{k,k}^\Delta) = \frac{k}{n-k},$$

provided $n \geq M_k$ where $M_k \in \mathbb{N}$ only depends on $k$.

Therefore, if we could claim that $\sigma_2(S_{k,k})$ of an arbitrary $\gamma$-HDX is close to $\sigma_2(S_{k,k}^\Delta)$ (provided $\gamma$ is sufficiently small), we would conclude that general $S_{k,k}$ walks are also expanding. A priori there is no reason why this claim should hold since a general $d$-sized $\gamma$-HDX may have much fewer hyperedges ($O_d(n)$ versus $\binom{n}{d}$) in the complete $\Delta_d(n)$). Fortunately, it turns out that this claim is indeed true (up to $O_k(\gamma)$ errors).

To prove Theorem V.1\(^4\) we employ the beautiful expanding poset (EPoset) machinery of Dikstein et al. [DDFH18]. Before we delve into the full technical analysis, it might be instructive to see how Theorem V.1 is obtained from understanding the quadratic form $\langle S_{k,k}f, f \rangle$ where $f \in C^k$.

First we informally recall the decomposition $C^k = \sum_{i=0}^k C^k_i$ from the EPoset machinery where $C^k_i$ can be thought of as the space of approximate eigenfunctions of degree $i$ of $C^k$ (the precise definitions are deferred to V-B). In this decomposition, $C^k_0$ is defined as the space of constant functions of $C^k$.

We prove the stronger result that the $S_{k,k}$ operators of any $\gamma$-HDX has an an approximate spectrum that only depends on $k$ provided $\gamma$ is small enough. More precisely, we prove Lemma V.6.

Lemma V.6 (Swap Quadratic Form). Let $f = \sum_{i=0}^k f_i$ with $f_i \in C^k_i$. Suppose $X(\leq d)$ is a $\gamma$-HDX with $d \geq 2k$. If $\gamma \leq \varepsilon \left(64k^{k+42k^2+1}\right)^{-1}$, then

$$\langle S_{k,k}f, f \rangle = \sum_{i=0}^k \lambda_k(i) \cdot \langle f_i, f_i \rangle \pm \varepsilon,$$

where $\lambda_k(i)$ depends only on $k$ and $i$, i.e., $\lambda_k(i)$ is an approximate eigenvalue of $S_{k,k}$ associated to space $C^k_i$.

Remark V.7. From Lemma V.6, it might seem that we are done since there exist approximate eigenvalues $\lambda_k(i)$ that only depend on $k$ and $i$. However, giving an explicit expression for these approximate eigenvalues is tricky. For this reason, we rely on the expansion of Kneser graphs as will be clear later.

Towards showing Lemma V.6, we introduce the notion of balanced operators which in particular captures canonical and swap walks and we show that the quadratic form expression of Lemma V.6 is a particular case of a general result for $(B \cdot f, f)$ where $B$ is a general balanced operator. A balanced operator in $C^k$ is any operator that can be obtained as linear combination of pure balanced operators, the later being operators that are a formal product of an equal number of up and down operators.

Lemma V.8 (General Quadratic Form). Let $\varepsilon \in (0,1)$ and let $Y \subseteq \{Y \mid Y: C^k \to C^k\}$ be a collection of formal operators that are product of an equal number of up and down walks (i.e., pure balanced operators) not exceeding $\ell$ walks. Let $B = \sum_{Y \in \mathcal{Y}} a^Y Y$ where $a^Y \in \mathbb{R}$ and let $f = \sum_{i=0}^k f_i$ with $f_i \in C^k_i$. If $\gamma \leq \varepsilon \left(16k^{k+2} \sum_{Y \in \mathcal{Y}} |a^Y| \right)^{-1}$, then

$$\langle Bf, f \rangle = \sum_{i=0}^k \left( \sum_{Y \in \mathcal{Y}} a^Y \lambda^Y_k(i) \right) \cdot \langle f_i, f_i \rangle \pm \varepsilon,$$

where $\lambda^Y_k(i)$ depends only on the operators appearing in the formal expression of $Y$, $i$ and $k$, i.e., $\lambda^Y_k(i)$ is the approximate eigenvalue of $Y$ associated to $C^k_i$.

Remark V.9. Note that our result generalizes the analysis of [DDFH18] for expanding posets of HDXs which
considered the particular case \( B = D_{k+1}U_k \). Moreover, their error term analysis treated all the parameters not depending on the number of vertices \( n \) as constants. In this work we make the dependence on the parameters explicit since this dependence is important in understanding the limits of our \( k \)-CSPs approximation scheme on HDXs. The beautiful EPoset machinery [DDFH18] is instrumental in our analysis.

Now, we are ready to prove Theorem V.1. For convenience we restate it below.

**Theorem V.10** (Swap Walk Spectral Bound (restatement of Theorem V.1)). Let \( X(\leq d) \) be a \( \gamma \)-HDX with \( d \geq 2k \). For every \( \sigma \in (0,1) \), if \( \gamma \leq \sigma \cdot \left(64k^k+42k+1\right)^{-1} \), then the second largest singular value \( \sigma_2(S_{k,k}) \) of the swap operator \( S_{k,k} \) is

\[
\sigma_2(S_{k,k}) \leq \sigma.
\]

**B. Expanding Posets and Balanced Operators**

We state the definitions used in our technical proofs starting with \( \gamma \)-EPoset from [DDFH18].

**Definition V.11** (\( \gamma \)-EPoset adapted from [DDFH18]). A complex \( X(\leq d) \) with operators \( U_0, \ldots, U_{d-1}, D_1, \ldots, D_d \) is said to be a \( \gamma \)-EPoset \(^5\) provided

\[
\|M_i^+-U_{i-1}D_i\|_{op} \leq \gamma, \tag{1}
\]

for every \( i = 1, \ldots, d-1 \), where

\[
M_i^+ := \frac{i+1}{i} \left(D_{i+1}U_i - \frac{1}{i+1}\right),
\]

i.e., \( M_i^+ \) is the non-lazy version of the random walk \( N_{i,i}^{(1)} = D_{i+1}U_i \).

**Definition V.11** can be directly used as an operational definition of high-dimension expansion as done in [DDFH18]. To us it is important that \( \gamma \)-HDXs are also \( \gamma \)-EPosets as established in Lemma V.12. In fact, these two notions are known to be closely related.

**Lemma V.12** (From [DDFH18]). Let \( X \) be a \( d \)-sized simplicial complex.

- If \( X \) is a \( \gamma \)-HDX, then \( X \) is a \( \gamma \)-EPoset.
- If \( X \) is a \( \gamma \)-EPoset, then \( X \) is a \( 3d \)-\( \gamma \)-HDX.

Naturally the complete complex \( \Delta_d(n) \) is a \( \gamma \)-EPoset since it is a \( \gamma \)-HDX. Moreover, in this particular case \( \gamma \) vanishes as \( n \) grows.

**Lemma V.13** (From [DDFH18]). The complete complex \( \Delta_d(n) \) is a \( \gamma \)-EPoset with \( \gamma = O_d \left(1/n\right) \).

\(^5\)We tailor their general EPoset definition to HDXs. In fact, what they call \( \gamma \)-HDX we call \( \gamma \)-EPoset. Moreover, what they call \( \gamma \)-HD expander we call \( \gamma \)-HDX.

**Harmonic Analysis on Simplicial Complexes:** The space \( C^0 \) defined in Section II-B2 can be decomposed into subspaces \( C_i^k \) of functions of degree \( i \) for \( 0 \leq i \leq k \) where

\[
C_i^k := \{U^k-ih_i \mid h_i \in H_i\},
\]

with \( H_i := \ker(D_i) \), and

\[
C_0^k := \{f : X(k) \rightarrow R \mid f \text{ is constant}\}.
\]

More precisely, we have the following.

**Lemma V.14** (From [DDFH18]).

\[
C_i^k = \sum_{i=0}^{k} C_i^k.
\]

For convenience set \( \delta_i = 1/(i+1) \) for \( i \in [d-1] \). It will also be convenient to work with the following equivalent version of Eq. (1)

\[
\|D_{i+1}U_i - (1 - \delta_i)U_{i-1}D_i - \delta_iI\|_{op} \leq \frac{i}{i+1}\gamma. \tag{2}
\]

Towards our goal of understanding quadratic forms of swap operators we study the approximate spectrum of operators of the form \( Y = Y_{\ell} \cdots Y_1 \) where each \( Y_i \) is either an up or down operator, namely, \( Y \) is a generalized random walk of \( \ell \) steps. We regard the expression \( Y_{\ell} \cdots Y_1 \) defining \( Y \) as a formal product.

**Definition V.15** (Pure Balanced Operator). We call \( Y : C^0 \rightarrow C^k \) a pure balanced operator if \( Y \) can be defined as product \( Y_{\ell} \cdots Y_1 \) \(^6\) where each \( Y_i \) is either an up or down operator. When we say that the spectrum of \( Y \) depends on \( Y \) we mean that it depends on \( k \) and on the formal expression \( Y_{\ell} \cdots Y_1 \) (i.e., pattern of up and down operators).

**Remark V.16.** By definition canonical walks \( N^{(u)}_{i,k} \) are pure balanced operators.

Taking linear combinations of pure balanced operators leads to the notion of balanced operators.

**Definition V.17** (Balanced Operator). We call \( B : C^k \rightarrow C^k \) a balanced operator provided there exists a set of pure balanced operators \( \mathcal{Y} \) such that

\[
B = \sum_{\mathcal{Y} \in \mathcal{Y}} \alpha^\mathcal{Y} \cdot Y_i
\]

where \( \alpha^\mathcal{Y} \in \mathbb{R} \).

**Remark V.18.** Corollary IV.13 establishes that \( S^{(u)}_{k,k} \) are balanced operators. In particular, \( S^{(u)}_{k,k} \) is a balanced operator.

It turns out that at a more crude level the behavior of \( Y \) is governed by how the number

\(^6\)For the analysis it is convenient to order the indices appearing in \( Y_{\ell} \cdots Y_1 \) in decreasing order from left to right.
of up operators compares to the number of down operators. For this reason, it is convenient to define \( U(Y) = \{ Y_t \mid Y_t \text{ is an up operator} \} \) and \( D(Y) = \{ Y_t \mid Y_t \text{ is a down operator} \} \) where \( Y \) is a pure balanced operator. When \( Y \) is clear in the context we use \( U = U(Y) \) and \( D = D(Y) \).

Henceforth we assume \( h_i \in H_i = \ker(D_i), f_i \in C_i^f \) and \( g \in C_i^f \). This convention will make the statements of the technical results of Section V-C cleaner.

C. Quadratic Forms over Balanced Operators

Now we establish all the technical results leading to and including the analysis of quadratic forms over balanced operators. By considering this general class of operators our analysis generalizes the analysis given in [DDFH18]. At the same time we refine their error terms analysis by making the dependence on the Eposet parameters explicit. Recall that an explicit dependence on these parameters is important in understanding the limits of our k-CSP approximation scheme.

Lemma V.19 (General Quadratic Form (restatement of Lemma V.8)). Let \( \epsilon \in (0,1) \) and let \( Y \subseteq \{ Y \mid Y : C^k \to C^f \} \) be a collection of formal operators that are product of an equal number of up and down walks (i.e., pure balanced operators) not exceeding \( \ell \) walks. Let \( B = \sum_{Y \in Y} a^Y \) where \( a^Y \in \mathbb{R} \) and let \( f = \sum_{i=0}^{k} f_i \) with \( f_i \in C_i^f \). If \( \gamma \leq \epsilon \left( 4k^k + 2^\ell \sum_{Y \in Y} |a^Y| \right)^{-1} \), then

\[
\langle Bf, f \rangle = \sum_{i=0}^{k} \left( \sum_{Y \in Y} a^Y \lambda^Y_k(i) \right) \cdot |f_i|^2 \pm \epsilon,
\]

where \( \lambda^Y_k(i) \) depends only on the operators appearing in the formal expression of \( Y \) and \( k, i.e., \lambda^Y_k(i) \) is the approximate eigenvalue of \( Y \) associated to \( C_i^f \).

Since swap walks are balanced operators, we will deduce the following.

Lemma V.20 (Swap Quadratic Form (restatement of Lemma V.6)). Let \( f = \sum_{i=0}^{k} f_i \) with \( f_i \in C_i^f \). Suppose \( X(\leq d) \) is a \( \gamma \)-HDX with \( d \geq 2k \). If \( \gamma \leq \epsilon \left( 4k^k + 2^\ell \sum_{i=0}^{k} |f_i|^2 \right)^{-1} \), then

\[
\langle S_{k,k}f, f \rangle = \sum_{i=0}^{k} \lambda_k(i) \cdot |f_i|^2 \pm \epsilon,
\]

where \( \lambda_k(i) \) depends on only on \( k \) and \( i \), i.e., \( \lambda_k(i) \) is an approximate eigenvalue of \( S_{k,k} \) associated to space \( C_i^f \).

The next result, Lemma V.21, (implicit in [DDFH18]) will be key in establishing that the spectral structure of \( \gamma \)-EPosets is fully determined by the parameters in \( \tilde{\delta} \) provided \( \gamma \) is small enough. Note that the Eposet Definition V.11 provides a “calculus” for rearranging a single pair of up and down DU. The next result treats the more general case of DU \( \cdots U \).

Lemma V.21 (Structure Lemma). Suppose \( |D| = 1 \). Let \( Y_c \in D \) be the unique down operator in \( Y, \ldots, Y_1 \). If \( \|A\|_{\text{op}} \leq 1 \), then

\[
\langle AY_1 \cdots Y_\ell h, g \rangle = \begin{cases} 0 & \text{if } \ell = 1 \text{ or } c = 1, \\ Q_{\tilde{\delta}}(\tilde{\delta}) \cdot (A \tilde{\delta} \cdot h, g) + (\ell - 1) \cdot \gamma \|h\| \|g\| & \text{otherwise,} \end{cases}
\]

where \( Q_{c,i} \) is a polynomial in the variables \( \tilde{\delta} \) depending on \( c, i \) such that \( Q_{c,i}(\tilde{\delta}) \leq 1 \).

With Lemma V.21 we are close to recover the approximate spectrum of \( D_{k+1}U_k \) from [DDFH18]. However, in our application we will need to analyze more general operators, namely, pure balanced and balanced operators.

Lemma V.22 (Refinement of [DDFH18]). If \( \|A\|_{\text{op}} \leq 1 \), then

\[
\langle AD_{k+1}U_k f, f \rangle = \lambda_i \cdot |f_i|^2 \pm s \cdot (k - i + 1) \cdot \gamma \|h_i\| \|f_i\|,
\]

where \( \lambda_i \) is given in Lemma V.22.

In case \( |D| > |U| \), \( Y : C^i \to C^f \) is an operator whose kernel approximately contains \( \ker(D_i) \) as the following lemma makes precise.

Lemma V.24 (Refinement of [DDFH18]). If \( \|D\| > \|U\| \) and \( h_i \in \ker(D_i) \), then

\[
\langle AY_1 \cdots Y_\ell h, g \rangle = \pm 2^\ell \cdot \gamma \|h_i\| \|g\|,
\]

provided \( \|A\|_{\text{op}} \leq 1 \).

We turn to an important particular case of \( |D| = |U| \), namely, the canonical walks. We show that \( N_{k,k}^{(2)} \) is approximately a polynomial in the operator \( D_{k+1}U_k \). As a warm up consider the case \( N_{k,k}^{(2)} = D_{k+1}D_{k+2}U_{k+1}U_k \). Using the Eq. (2), we get

\[
N_{k,k}^{(2)} \approx (1 - \delta_{k+1}) \cdot D_{k+1}U_k D_{k+1}U_k + \delta_{k+1} \cdot D_{k+1}U_k \approx (1 - \delta_{k+1}) \cdot (D_{k+1}U_k)^2 + \delta_{k+1} \cdot D_{k+1}U_k.
\]

Inspecting this polynomial more carefully we see that its coefficients form a probability distribution. This
property holds in general as the following Lemma V.25 shows. This gives an alternative (approximate) random walk interpretation of $N^{(u)}_{k,k}$ as the walk that first selects the power $s$ according to the distribution encoded in the polynomial and then moves according to $(D_{k+1}U_k)^s$.

**Lemma V.25** (Canonical Polynomials). For $k,u \geq 0$ there exists a degree $u$ univariate polynomial $F^N_{u,k,\delta}$ depending only on $u,k,\delta$ such that

$$\|N^{(u)}_{k,k} - F^N_{u,k,\delta}(D_{k+1}U_k)\|_{op} \leq (u-1)^2 \cdot \gamma.$$

Moreover, the coefficients of this polynomial form a probability distribution, i.e., $F^N_{u,k,\delta}(x) = \sum_{i=0}^u c_i x^i$ where $\sum_{i=0}^u c_i = 1$ and $c_i \geq 0$ for $i = 0,\ldots,u$.

**Remark V.26.** Having a polynomial expression $F^N_{u,k,\delta}(D_{k+1}U_k) \approx N^{(u)}_{k,k}$ and knowing that $S_{k,k}$ can be written as linear combination of canonical walks, we could deduce that $S_{k,k}$ is also approximately a polynomial in $D_{k+1}U_k$. Using an error refined version of the Lemma V.23 (showing that exponentiation of $D_{k+1}U_k$ behaves naturally), we could deduce the approximate spectrum of $S_{k,k}$. We avoid this approach since it analysis introduces unnecessary error terms and we can understand quadratic forms of pure balanced operators directly.

**Remark V.27.** The canonical polynomial $F^N_{u,k,\delta}(D_{k+1}U_k)$ is used later in the error analysis that relates the norms $\|h_i\|$ and $\|f_i\|$ (Lemma V.30).

Now we consider $Y$ where $|D| = |U|$ in full generality. We show how the quadratic form of $Y$ behaves in terms of the approximate eigenspace decomposition $C^k = \sum_{i=0}^k C_i$.

**Lemma V.28** (Pure Balanced Walks). Suppose $Y = Y_1 \ldots Y_1$ is a product of an equal number of up and down operators, i.e., $|D| = |U|$. Then for $f_i \in C^k$

$$\langle Y f_i, f_i \rangle = \lambda^Y_{f_i} \cdot (f_i, f_i) \pm \gamma \cdot (\ell^2 + \ell(k-i-1)) \|h_i\| \|f_i\|,$$

where $\lambda^Y_{f_i}$ is an approximate eigenvalue depending only on $Y$ and $i$.

To understand all errors in the analysis in Lemma V.28, we need to use the approximate orthogonality of $f_i$ and $f_j$ for $i \neq j$ from [DDFH18] in more detail. We start with the following bound in terms of $h_i, h_j$.

**Lemma V.29** (Refinement of [DDFH18]). For $i \neq j$,

$$\langle f_i, f_j \rangle = \pm (2k - j - i)^2 \cdot \gamma \|h_i\| \|h_j\|.$$

To give a bound for Lemma V.29 only in terms of the eigenfunction norms $\|f_i\|$ and not in terms of $\|h_i\|$,

we need to understand how the norms of $h_i$ and $f_i$ are related.

**Lemma V.30** (Refinement of [DDFH18]). Let $\eta_{k,i} = (k-i)^2 + 1$ and let $\beta_i = \sqrt{\frac{\sum_{i=0}^u c_i x^i}{\sum_{i=0}^u c_i x^i}}$ for $i = 0,\ldots,u$.

Let $\theta_{k,i} = (i+1)^{k-i}$. Furthermore, if $\gamma \leq \min \{1/(2 \cdot \eta_{k,i} \cdot \theta_{k,i}), 1/(2 \cdot \eta_{k,i} \cdot \theta_{k,i})\}$, then $\beta_i \geq \frac{1}{2\theta_{k,j}}$.

Now, we can state the approximate orthogonality Lemma V.31 in terms of the eigenfunction norms.

**Lemma V.31** (Approximate Orthogonality (refinement of [DDFH18])). Let $\eta_{k, i} \theta_{i, s \pm} \beta_s$ for $s \in \{i, j\}$ be given as in Lemma V.30. If $i \neq j$ and $\beta_i, \beta_j > 0$, then

$$\langle f_i, f_j \rangle = \pm \gamma \cdot \lambda^Y_{f_i} \cdot \lambda^Y_{f_j} \cdot (2k - j - i)^2 \|f_i\| \|f_j\|.$$

Furthermore, if $\gamma \leq \min \{1/(2 \cdot \eta_{k,i} \cdot \theta_{k,i}), 1/(2 \cdot \eta_{k,i} \cdot \theta_{k,i})\}$, then $\beta_i, \beta_j \geq 0$ and

$$\langle f_i, f_j \rangle \leq \gamma \cdot \theta_{k,i} \cdot \theta_{k,j} \cdot (2k - i - j)^2 \|f_i\| \|f_j\|.$$

We generalize the quadratic form of Lemma V.28 to linear combinations of general pure balanced operators $Y$, namely, to balanced operators.

**Lemma V.32** (General Quadratic Form (restatement of Lemma V.8)). Let $\epsilon \in (0,1)$ and let $Y \subseteq \{ Y \mid Y : C^k \rightarrow C^k \}$ be a collection of formal operators that are product of an equal number of up and down walks (i.e., pure balanced operators) not exceeding $\ell$ walks. Let $B = \sum_{Y \in \mathcal{Y}} a^Y Y$ where $a^Y \in \mathbb{R}$ and let $f = \sum_{i=0}^k f_i$ with $f_i \in C^k$. If $\gamma \leq \epsilon \left( 16k^2 + 2^2 \sum_{Y \in \mathcal{Y}} |a^Y| \right)^{-1}$, then

$$\langle B f, f \rangle = \sum_{i=0}^k \left( \sum_{Y \in \mathcal{Y}} a^Y \lambda^Y_{f_i} \right) \cdot \langle f_i, f_i \rangle \pm \epsilon,$$

where $\lambda^Y_{f_i}$ depends only on the operators appearing in the formal expression of $Y$, $i$ and $k$, i.e., $\lambda^Y_{f_i}$ is the approximate eigenvalue of $Y$ associated to $C_i$.

We instantiate Lemma V.31 for swap walks with their specific parameters. First, we introduce some notation. Using Corollary IV.15, we have

$$S_{k,k} = \sum_{j=0}^k (-1)^{k-j} \cdot \binom{k+j}{k} \cdot \binom{k}{j} \cdot N_{i,k,k} = \sum_{j=0}^k a_j \cdot N_{i,k,k},$$

where $a_j = (-1)^{k-j} \cdot \binom{k+j}{k} \cdot \binom{k}{j}$. 

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Finally, we have all the pieces to prove Lemma V.6
restated below.

Lemma V.33 (Swap Quadratic Form (restatement of Lemma V.6)). Let \( f = \sum_{i=0}^{k} f_i \) with \( f_i \in C_i \).
Suppose \( X(\leq d) \) is a \( \gamma \)-HDX with \( d \geq 2k \). If \( \gamma \leq \varepsilon \left( \frac{64k^2+2k^2+1}{1} \right)^{-1} \), then
\[
\langle S_{k,k} f, f \rangle = \sum_{i=0}^{k} \lambda_k(i) \cdot (f_i, f_i) \approx \varepsilon,
\]
where \( \lambda_k(i) \) depends on only on \( k \) and \( i \), i.e., \( \lambda_k(i) \) is an approximate eigenvalue of \( S_{k,k} \) associated to space \( C_i \).

D. Rectangular Swap Walks \( S_{k,l} \)

We turn to the spectral analysis of rectangular swap walks, i.e., \( S_{k,l} \) where \( k \neq l \). Recall that to bound \( \sigma(\langle S_{k,k} \rangle) \) in Section V-A we proved that the spectrum of \( S_{k,k} \) for a \( \gamma \)-HDX is close to the spectrum of \( S_{k,k}^\Delta \) using the analysis of quadratic forms over balanced operators from Section V-C. Then we appealed to the fact that \( S_{k,k}^\Delta \) is expanding since it is the walk operator of the well known Kneser graph. In this rectangular case, we do not have a classical result establishing that \( S_{k,l}^\Delta \) is expanding, but we were able to establish it Lemma V.34.

Lemma V.34. Let \( d \geq k+l \) and \( \Delta_d(n) \) be the complete complex. The second largest singular value \( \sigma_2(S_{k,l}^\Delta) \) of the swap operator \( S_{k,l}^\Delta \) on \( \Delta_d(n) \) is
\[
\sigma_2(S_{k,l}^\Delta) = \max \left( \frac{k}{n-l', n-l} \right),
\]
provided \( n \geq M_{k,l} \) where \( M_{k,l} \in \mathbb{N} \) only depends on \( k \) and \( l \).

Towards proving Lemma V.34 we first introduce a generalization of Kneser graphs which we denote bipartite Kneser graphs defined as follows.

Definition V.35 (General Bipartite Kneser Graph). Let \( X(\leq d) \) where \( d \geq k+l \). We denote by \( K^X(n,k,l) \) the bipartite graph on (vertex) partition \( (X(k), X(l)) \) where \( s \in X(k) \) is adjacent to \( t \in X(l) \) if and only if \( s \cap t \) is empty. We also refer to graphs of the form \( K^X(n,k,l) \) as bipartite Kneser graphs.

It will be convenient to distinguish bipartite Kneser graphs coming from general \( \gamma \)-HDX and the complete complex \( \Delta_d(n) \).

Definition V.36 (Complete Bipartite Kneser Graph). Let \( X(\leq d) \) where \( d \geq k+l \). If \( X \) is the complete complex, i.e., \( X = \Delta_d(n) \), then we denote \( K^{\Delta}(n,k,l) \) as simply as \( K(n,k,l) \) and we refer to it as complete bipartite Kneser.

We obtain the spectra of bipartite Kneser graphs generalizing \(^7\) the classical result of Fact V.4. More precisely, we prove Lemma V.37.

Lemma V.37 (Bipartite Kneser Spectrum). The non-zero eigenvalues of the (normalized) walk operator of \( K(n,k,l) \) are \( \pm \lambda_i \) where
\[
\lambda_i = \frac{(n-k-i)(n-l-i)}{(n-k)(n-l)},
\]
for \( i = 0, \ldots, \min(k,l) \).

Now the proof follows a similar strategy to the \( S_{k,k} \), namely, we analyze quadratic forms over \( S_{k,l} \) using the results from Section V-C.

Let \( X(\leq d) \) where \( d \geq k+l \). Let \( A_{k,l} \) be the (normalized) walk operator of \( K^X(n,k,l) \), i.e.,
\[
A_{k,l} = \left( \begin{array}{c} \left( S_{k,l}^\Delta \right) \left( S_{k,l}^\Delta \right)^\dagger \\ 0 \end{array} \right).
\]

To determine the spectrum of \( A_{k,l} \) it is enough to consider the spectrum of \( B = S_{k,l}^\Delta \left( S_{k,l}^\Delta \right)^\dagger \). Using Corollary IV.13, we have
\[
B = \left( \sum_{j=0}^{l} (-1)^{i-j} \binom{k+j}{l} \cdot \binom{j}{i} \cdot \left( N_{k,l}^{(l)} \right)^\dagger \right),
\]
for some coefficients \( a_{k,j,l}^j \) depending only on \( k \), \( l \), \( i \), and \( j' \). Since we have not yet used any specific property of HDXs, these coefficients are the same for the complete complex and general HDXs.

Lemma V.38. Let \( X(\leq d) \) be a \( \gamma \)-HDX with \( d \geq k+l \). Let \( f = \sum_{i=0}^{k} f_i \) with \( f_i \in C_i \). For \( \varepsilon \in (0,1) \), if \( \gamma \leq \varepsilon \left( \frac{64k^2+2k^2+1}{1} \right)^{-1} \), then
\[
\langle B f, f \rangle = \sum_{i=0}^{k} \left( \sum_{j=0}^{l} a_{k,j,l}^j \lambda_{k,j,l}^j (i) \right) \cdot (f_i, f_i) + \varepsilon,
\]
where \( \lambda_{k,j,l}^j (i) \) is the approximate eigenvalues of \( N_{k,l}^{(l)} N_{k,l}^{(j')} \) corresponding to space \( C_i \). Furthermore, \( \lambda_{k,j,l}^j (i) \) depends only on \( k \), \( l \), \( i \), and \( j' \).

Note that the singular values of \( K(n,k) \) can be deduced from the bipartite case.
Let $B$ and $B^A$ stand for the $B$ operator for general \(\gamma\)-HDX and the complete complex, respectively.

**Lemma V.39.** Suppose \(X(\leq d)\) is a \(\gamma\)-HDX with \(d \geq k + l\). For \(\varepsilon \in (0,1)\), if \(\gamma \leq \varepsilon^2 \left(64k^2 + 2^k2^{k+4l+2}\right)^{-1}\), then the second largest singular value \(\sigma_2(B)\) of the walk matrix of \(K(n,k,l)\) is

\[
\sigma_2(B) \leq \varepsilon^2.
\]

Furthermore, the second largest non-trivial eigenvalue \(\lambda(A_{k,l})\) of the walk matrix of \(K(n,k,l)\) is

\[
\lambda(A_{k,l}) \leq \varepsilon.
\]

Now the proof of **Theorem V.2** follows. For convenience, we restate it.

**Theorem V.40 (Rectangular Swap Walk Spectral Bound (restatement of Theorem V.2)).** Suppose \(X(\leq d)\) is a \(\gamma\)-HDX with \(d \geq k + l\) and \(k \leq l\). For \(\sigma \in (0,1)\), if \(\gamma \leq \sigma^2 \cdot \left(64k^2 + 2^k2^{k+4l+2}\right)^{-1}\), then the largest non-trivial singular value \(\sigma_2(S_{k,l})\) of the swap operator \(S_{k,l}\) is

\[
\sigma_2(S_{k,l}) \leq \sigma.
\]

**E. Bipartite Kneser Graphs - Complete Complex**

Now we determine the spectrum of the complete bipartite Kneser graph \(K(n,k,l)\). More precisely, we prove the following.

**Lemma V.41 (Bipartite Kneser Spectrum (restatement of Lemma V.37)).** The non-zero eigenvalues of the normalized walk operator of \(K(n,k,l)\) are \(\pm \lambda_i\) where

\[
\lambda_i = \frac{(n-k-i)(n-l-i)}{(l-i)(n-l)}.
\]

for \(i = 0, \ldots, \min(k,l)\).

Henceforth, set \(X = \Delta_d(n)\). To prove **Lemma V.37** we work with the natural rectangular matrix associated with \(K(n,k,l)\), namely, the matrix \(W \in \mathbb{R}^{X(k) \times X(l)}\) such that

\[
W(s,t) = \mathbb{I}_{[s \cap t = \emptyset]}
\]

for every \(s \in X(k)\) and \(t \in X(l)\).

Observe that the entries of \(WW^T\) and \(W^TW\) only depend on the size of the intersection of the sets indexing the row and columns. Hence, these matrices belong to the Johnson scheme \([GM15]\) \(J(n,k)\) and \(J(n,l)\), respectively. Moreover, the left and right singular vectors of \(W\) are eigenvectors of these schemes.

We adopt the eigenvectors used in Filmus’ work \([Fil16]\), i.e., natural basis vectors coming from some irreducible representation of \(S_n\) (see \([Sag13]\)). First we introduce some notation. Let \(\mu = (n-i,i)\) be a partition of \(n\) and let \(\tau_{\mu}\) be a standard tableau of shape \(\mu\). Suppose the first row \(\tau_{\mu}\) contains \(a_1 < \cdots < a_{n-i}\), whereas the second contains \(b_1 < \cdots < b_i\). To \(\tau_{\mu}\) we associate the function \(\varphi_{\tau_{\mu}} \in \mathbb{R}^{(n)}\) as follows

\[
\varphi_{\tau_{\mu}} = (1_{a_1} - 1_{b_1}) \cdots (1_{a_i} - 1_{b_i}),
\]

where \(1_a \in \mathbb{R}^{(i)}\) is the containment indicator of element \(a\), i.e., \(1_a(s) = 1\) if and only if \(a \in s\). Filmus proved that

\[
\left\{ \varphi_{\tau_{\mu}} \mid 0 \leq i \leq k, \mu = (n-i,i), \tau_{\mu} \text{ standard} \right\}
\]

is an eigenbasis of \(J(n,k)\). We abuse the notation by considering \(\varphi_{\tau_{\mu}}\) as both a function in \(\mathbb{R}^{(i)}\) and \(\mathbb{R}^{(l)}\) as long as these functions are well defined.

**Claim V.42.** If \(\mu = (n-i,i)\) and \(k,l \geq i\), then

\[
W \varphi_{\tau_{\mu}} = (-1)^l \cdot \binom{n-k-i}{l-i} \cdot \varphi_{\tau_{\mu}}.
\]

Since we are working with singular vectors, we need to be careful with their normalization when deriving the singular values. We stress that the norm of \(\varphi_{\tau_{\mu}}\) depends on the space where \(\varphi_{\tau_{\mu}}\) lies.

**Claim V.43.** If \(\mu = (n-i,i)\) and \(\varphi_{\tau_{\mu}} \in \mathbb{R}^{(i)}\), then

\[
\left\| \varphi_{\tau_{\mu}} \right\|_2 = 2^i \cdot \binom{n-2i}{k-i}.
\]

Now the singular values of \(W\) follow.

**Corollary V.44 (Singular Values).** The singular values of \(W\) are

\[
\sigma_i = \binom{n-k-i}{l-i} \cdot \left\| \varphi^k_{\tau_{\mu}} \right\|_2 \cdot \left\| \varphi^l_{\tau_{\mu}} \right\|_2,
\]

for \(i = 0, \ldots, \min(k,l)\).

Note that for \(k = l\) we recover the well know result of **Fact V.4**.

Finally we compute the eigenvalues of the bipartite graph \(K(n,k,l)\). Let \(A_{n,k,l}\) be its normalized adjacency matrix, i.e.,

\[
A_{n,k,l} = \left(\begin{array}{cc} 0 & W^T \binom{n-1}{k-1} \\ \binom{n-1}{k-1} W^T & 0 \end{array} \right).
\]

**Lemma V.45 (Bipartite Kneser Spectrum (restatement of Lemma V.37)).** The non-zero eigenvalues of the normalized walk operator of \(K(n,k,l)\) are \(\pm \lambda_i\) where

\[
\lambda_i = \binom{n-k-i}{l-i} \cdot \binom{n-l-i}{k-i},
\]

for \(i = 0, \ldots, \min(k,l)\).
VI. APPROXIMATING MAX-k-CSP

In the following, we will show that k-CSP instances \( J \) whose constraint complex \( X_J(\leq k) \) is a suitable expander admit an efficient approximation algorithm. We will assume throughout that \( X_J(1) = [n] \), and drop the subscript \( J \).

This was shown for 2-CSPs in [BRS11]. In extending this result to k-CSPs we will rely on a central Lemma of their paper. Before, we explain our algorithm we give a basic outline of our idea:

We will work with the SDP relaxation for the k-CSP problem given by \( \ell \)-levels of SoS hierarchy, as defined in Section II-D (for \( \ell \) to be specified later). This will give us an \( \ell \)-local PSD ensemble \( \{ Y_1, \ldots, Y_n \} \), which attains some value \( \text{SDP}(J) \geq \text{OPT}(J) \). Since \( \{ Y_1, \ldots, Y_n \} \) is a local PSD ensemble, and not necessarily a probability distribution, we cannot sample from it directly. Nevertheless, since \( \{ Y_1 \} \) will be actual probability distributions for all \( j \in [n] \), one can independently sample \( \eta_j \sim \{ Y_j \} \) and use \( \eta = (\eta_1, \ldots, \eta_n) \) as the assignment for the k-CSP instance \( J \).

Unfortunately, while we know that the local distributions \( \{ Y_a \}_{a \in X(k)} \) induced by \( \{ Y_1, \ldots, Y_n \} \) will satisfy the constraints of \( J \) with good probability, i.e.,

\[
\mathbb{E}_{a \sim \Pi_k} \mathbb{E}_{\{ Y_a \} \text{satisfies the constraint on } a} = \text{SDP}(J) \geq \text{OPT}(J),
\]

this might not be the case for the assignment \( \eta \) sampled as before. It might be that the random variables \( Y_{a_1}, \ldots, Y_{a_k} \) are highly correlated for \( a \in X(k) \), i.e., \( \mathbb{E}_{a \sim \Pi_k} \left\| \{ Y_{a_1} \} - \{ Y_{a_2} \} \cdot \{ Y_{a_3} \} \right\|_1 \) is large. One strategy employed by [BRS11] to ensure that the quantity above is small, is making the local PSD ensemble \( \{ Y_1, \ldots, Y_n \} \) be consistent with a randomly sampled partial assignment for a small subset of variables (q.v. Section II-D). We will show that this strategy is successful if \( X(\leq k) \) is a \( \gamma \)-HDX (for \( \gamma \) sufficiently small). Our final algorithm is Algorithm VI.1.

In our setting, we will apply Algorithm VI.1 with the distribution \( \Pi_k \) and the \( \ell \)-local PSD ensemble \( \{ Y_1, \ldots, Y_n \} \). Notice that in expectation, the marginals of \( Y' \) on faces \( a \in X(k) \) are actual distributions – will agree with the marginals of \( Y \), i.e. \( \mathbb{E}_{Y(a \in X(k))} = \mathbb{E}_{Y_a} = \mathbb{E}_{Y} \). In particular, the approximation quality of Algorithm VI.1 will depend on the average correlation of \( Y_{a_1}, \ldots, Y_{a_k} \) on the constraints \( a \in X(k) \), where \( Y' \) is the local PSD ensemble obtained at the end of the first phase of Algorithm VI.1.

In the case where \( k = 2 \), the following is known

**Theorem VI.1.2 (Theorem 5.6 from [BRS11]).** Suppose a weighted undirected graph \( G = ([n], E, \Pi_2) \) and an \( \ell \)-local PSD ensemble \( Y = \{ Y_1, \ldots, Y_n \} \) are given. There exists absolute constants \( c \geq 0 \) and \( C \geq 0 \) satisfying the following: If \( L \geq c \cdot q^2 \), \( \text{Supp}(Y) \leq q \) for all \( i \in V \), and \( \lambda_2(G) \leq C \cdot q^2 / q^2 \) then we have

\[
\mathbb{E}_{\{ Y_i \} \sim \Pi_2} \| \{ Y'_i \} - \{ Y'_i \} \{ Y'_j \} \|_1 \leq \varepsilon,
\]

where \( Y' \) is as defined in Algorithm VI.1 on the input of \( \{ Y_1, \ldots, Y_n \} \) and \( \Pi_1 \).

To approximate k-CSPs well, we will show the following generalization of Theorem VI.1.2 for k-CSP instances \( J \), whose constraint complex \( X(\leq k) \) is a \( \gamma \)-HDX, for \( \gamma \) sufficiently small.

**Theorem VI.3.** Suppose a simplicial complex \( X(\leq k) \) with \( X(1) = [n] \) and an \( \ell \)-local PSD ensemble \( Y = \{ Y_1, \ldots, Y_n \} \) are given.

There exists some universal constants \( c' \geq 0 \) and \( C' \geq 0 \) satisfying the following: If \( L \geq c' \cdot (q^2 \cdot k^2 / \epsilon^4) \), \( \text{Supp}(Y) \leq q \) for all \( j \in [n] \), and \( X \) is a \( \gamma \)-HDX for \( \gamma \leq C' \cdot q^2 / (k^{8+k} \cdot 2^{6k} \cdot q^{2k}) \). Then, we have

\[
\mathbb{E}_{a \sim \Pi_k} \| \{ Y_a \} - \{ Y'_a \} \{ Y'_a \} \|_1 \leq \varepsilon,
\]

where \( Y' \) is as defined in Algorithm VI.1 on the input of \( \{ Y_1, \ldots, Y_n \} \) and \( \Pi_k \).

Indeed, using Theorem VI.3, it is straightforward to prove the following,

**Corollary VI.4.** Suppose \( J \) is a q-ary k-CSP instance whose constraint complex \( X(\leq k) \) is a \( \gamma \)-HDX.

There exists absolute constants \( C' \geq 0 \) and \( c' \geq 0 \), satisfying the following: If \( \gamma \leq C' \cdot q^2 / (k^{8+k} \cdot 2^{6k} \cdot q^{2k}) \), there is an algorithm that runs in time \( n^{O(k^3 \cdot q^2 \cdot \epsilon^{-4})} \) based
on (\(\epsilon^\ell, \ell^d\))-levels of SoS-hierarchy and Algorithm VI.1 that outputs a random assignment \(\eta : [n] \to [q]\) that in expectation ensures \(\text{SAT}_3(\eta) = \text{OPT}(\eta) - \epsilon\).

Our proof of Theorem VI.3\(^8\) will hinge on the fact that we can upper-bound the expected correlation of a face of large cardinality \(\ell\), in terms of expected correlation over faces of smaller cardinality and expected correlations along the edges of a swap graph. The swap graph here is defined as a weighted graph \(G_{\ell_1,\ell_2} = (X(\ell_1) \cup X(\ell_2), E(\ell_1, \ell_2), w_{\ell_1,\ell_2})\), where

\[
E(\ell_1, \ell_2) = \{a, b) : a \in X(\ell_1), b \in X(\ell_2), \text{ and } a \sqcup b \in X(\ell_1 + \ell_2)\}.
\]

We will assume \(\ell_1 \geq \ell_2\), and if \(\ell_1 = \ell_2\) we are going to identify the two copies of every vertex. We will endow \(E(\ell_1, \ell_2)\) with the weight function

\[
w_{\ell_1,\ell_2}(a, b) = \frac{\Pi_{\ell_1 + \ell_2}(a \sqcup b)}{(\ell_1 + \ell_2)},
\]

which can easily be verified to be a probability distribution on \(E(\ell_1, \ell_2)\). Notice that in the case where \(\ell_1 \neq \ell_2\) the random walk matrix of \(G_{\ell_1,\ell_2}\) is given by

\[
A_{\ell_1,\ell_2} = \begin{pmatrix} 0 & S_{\ell_1,\ell_2} \\ S_{\ell_1,\ell_2}^T & 0 \end{pmatrix},
\]

and if \(\ell_1 = \ell_2\) we have \(A_{\ell_1,\ell_1} = S_{\ell_1,\ell_1}\). The stationary distribution of \(A_{\ell_1,\ell_2}\) is \(\Pi_{\ell_1,\ell_2}\), defined by

\[
\Pi_{\ell_1,\ell_2}(b) = \frac{1}{2} \left[ \Pi_{\ell_1}(b) + \frac{1}{|X(\ell_2)|} \cdot \Pi_{\ell_2}(b) \right].
\]

When we write an expectation of \(f(\bullet, \bullet)\) over the edges in \(E(\ell_1, \ell_2)\) with respect to \(w_{\ell_1,\ell_2}\), it is important to note,

\[
\mathbb{E}_{(s, t) \sim w_{\ell_1,\ell_2}} [f(s, t)] = \sum_{(s, t) \in E(\ell_1, \ell_2)} \frac{\Pi_{\ell_1 + \ell_2}(s \sqcup t)}{(\ell_1 + \ell_2)} \cdot f(s, t),
\]

\[
= \frac{1}{(\ell_1 + \ell_2)} \mathbb{E}_{a \sim \Pi_{\ell_1}} \left[ \sum_{s, t \sim a} f(s, t) \right],
\]

where sum within the expectation in the RHS runs over the \((\ell_1 + \ell_2)\) possible ways of splitting a into \(s \sqcup t\) such that \(s \in X(\ell_1)\) and \(t \in X(\ell_2)\). When we are speaking about the spectral expansion of \(G_{\ell_1,\ell_2}\), we will be speaking with regards to \(\lambda_2(G_{\ell_1,\ell_2})\) and not with regards to \(\sigma_2(G_{\ell_1,\ell_2})\).

**Remark VI.5.** By simple linear algebra, we have

\[
\lambda_2(G_{\ell_1,\ell_2}) := \lambda_2(A_{\ell_1,\ell_2}) \leq \sigma_2(S_{\ell_1,\ell_2}),
\]

where we employ the notation \(\lambda_2(M)\) to denote the second largest eigenvalue (signed) of the matrix \(M\).

\(\text{with this, we will show Lemma VI.6 (Glorified Triangle Inequality). For a simplistic complex } X(\leq k), \ell_1 \geq \ell_2 \geq 0, \ell = \ell_1 + \ell_2, \ell \leq k, \text{ and an } \ell\text{-local ensemble } \{Y_1, \ldots, Y_n\}, \text{ one has}

\[
\mathbb{E}_{a \sim \Pi_\ell} \left[ \|Y_a - \Pi_\ell Y_i\|_1 \right] \leq \mathbb{E}_{a \sim \Pi_\ell} \left[ \|Y_a - Y_i\|_1 \right] + \mathbb{E}_{a \sim \Pi_\ell} \left[ \|Y_a - Y_i\|_1 \right] + \mathbb{E}_{a \sim \Pi_\ell} \left[ \|Y_i - Y_i\|_1 \right].
\]

One useful observation, is that by using Lemma VI.6 repeatedly, we can reduce the problem of bounding \(\mathbb{E}_{a \sim \Pi_\ell} \left[ \|Y_a - \Pi_\ell Y_i\|_1 \right]\) to a problem of bounding \(\mathbb{E}_{a \sim \Pi_\ell} \left[ \|Y_a - Y_i\|_1 \right]\) for \(\ell_1 + \ell_2 \leq k\). Though it is not a direct implication, it is heavily suggested by Fact II.7 and Theorem VI.2, that if \(G_{\ell_1,\ell_2}\) is a good spectral expander, after an application of Algorithm VI.1 with our chosen parameters, we should be able to bound these expressions. Using a key lemma used from [BRS11], we will prove that this is indeed the case. The only thing we need to make sure after this point, is that the second eigenvalue \(\lambda_2(G_{\ell_1,\ell_2})\) of the swap graphs \(G_{\ell_1,\ell_2}\) we will be using are small enough for our purposes. Indeed, our choice of \(\gamma\) in Theorem VI.3 and Corollary VI.4 is to make sure that the bound we get on \(\lambda_2(G_{\ell_1,\ell_2})\) from Theorem V.2 (together with Remark VI.5) is good enough for our purposes.

**A. Breaking Correlations for Expanding CSPs**

Throughout this section, we will use the somewhat non-standard definition of variance introduced in [BRS11],

\[
\text{Var}[Y_a] = \sum_{\eta \in [q]^n} \text{Var}[I[Y_a = \eta]].
\]

We will use the following central lemma from [BRS11] in our proof of Theorem VI.3:

**Lemma VI.7 (Lemma 5.4 from [BRS11]).** Let \(G = (V, E, \Pi_\ell)\) be a weighted graph, \(\{Y_1, \ldots, Y_n\}\) a local PSD ensemble, where we have \(\text{Supp}(Y_i) \leq q\) for every \(i \in V\), and \(q \geq 0\). Suppose \(\epsilon \geq 0\) is a lower bound on the expected statistical difference between independent and correlated sampling along the edges, i.e.,

\[
\epsilon \leq \mathbb{E}_{(i,j) \sim \Pi_\ell} \left[ \|Y_{ij} - Y_i Y_j\|_1 \right].
\]

There exists absolute constants \(c_0 \geq 0\) and \(c_1 \geq 0\) that satisfy the following: If \(\lambda_2(G) \leq c_0 \cdot \epsilon^2 \cdot q^{-1}\), then, conditioning
on a random vertex decreases the variances,
\[ E_{i \sim I_{1}} E_{j \sim I_{2}} \text{Var}[Y_{i} | Y_{j}] \leq E_{i \sim I_{1}} \text{Var}[Y_{i}] - c_{1} \cdot \frac{\epsilon^{2}}{q^{2}}. \]

For our applications, we will be instantiating Lemma VI.7 with \( G_{i_{1}, i_{2}} \) as \( G \) and with the local PSD ensemble \( \{Y_{a}\}_{a \in X} \) that is obtained from \( \{Y_{1}, \ldots, Y_{n}\} \) (q.v. Fact II.7). For convenience, we will write the concrete instance of the Lemma that we will use,

**Corollary VI.8.** Let \( \ell_{1} \geq \ell_{2} \geq 0 \) satisfying \( \ell_{1} + \ell_{2} \leq k \) be given parameters, and let \( G_{i_{1}, i_{2}} \) be the swap graph defined for a \( \gamma \)-HDX \( X(\leq k) \). Let \( \{Y_{a}\}_{a \in X} \) be a local PSD ensemble; satisfying \( \text{Supp}(Y_{a}) \leq q^{a} \) for every \( a \in X(\ell_{1}) \cup X(\ell_{2}) \) for some \( q \geq 0 \). Suppose \( \epsilon \geq 0 \) satisfies,
\[ \frac{\epsilon}{4k} \leq E_{(s, t) \in w_{i_{1}, i_{2}}} \|\{Y_{s, t}\} - \{Y_{b}\}\{Y_{b}\}\|_{1}. \]

There exists absolute constants \( c_{0} \geq 0 \) and \( c_{2} \geq 0 \) that satisfy the following: If \( \lambda_{2}(G) \leq c_{0} \cdot (\epsilon/(4k \cdot q^{a}))^{2} \). Then, conditioning on a random face \( a \sim \Pi_{i_{1}, i_{2}} \) decreases the variances, i.e.,
\[ E_{a, b \sim \Pi_{i_{1}, i_{2}}} \text{Var}[Y_{b} | Y_{a}] \leq E_{b \sim \Pi_{i_{1}, i_{2}}} \text{Var}[Y_{b}] - c_{2} \cdot \frac{\epsilon^{2}}{16 \cdot k^{2} \cdot q^{2k}}. \]

Here, it can be verified that the expansion criterion presupposed by Lemma VI.7 is satisfied by Corollary VI.8 by Theorem V.2.

### VII. High-Dimensional Threshold Rank

In [BRS11], Theorem VI.2 was proven for a more general class of graphs than expander graphs – namely, the class of low threshold rank graphs.

**Definition VII.1** (Threshold Rank of Graphs (from [BRS11])). Let \( G = (V, E, w) \) be a weighted graph on \( n \) vertices and \( A \) be its normalized random walk matrix. Suppose the eigenvalues of \( A \) are \( 1 = \lambda_{1} \geq \cdots \geq \lambda_{n} \). Given a parameter \( \tau \in (0, 1) \), we denote the threshold rank of \( G \) by \( \text{rank}_{\geq \tau}(A) \) (or \( \text{rank}_{\geq \tau}(G) \)) and define it as
\[ \text{rank}_{\geq \tau}(A) := |\{i | \lambda_{i} \geq \tau\}|. \]

There [BRS11], the authors asked for the correct notion of threshold rank for \( k \)-CSPs. In this section, we give a candidate definition of low threshold rank motivated by our techniques.

To break \( k \)-wise correlations it is sufficient to assume that the involved swap graphs in the foregoing discussion are low threshold rank since this is enough to apply a version of Lemma VI.7, already described in the work of [BRS11].

Moreover, we have some flexibility as to which swap graphs to consider as long as they satisfy some splitting conditions. To define a swap graph it is enough to have a distributions on the hyperedges of a (constraint) hypergraph. Hence, the notion of swap graph is independent of high-dimensional expansion. HDXs are just an interesting family of objects for which the swap graphs are good expanders.

To capture the many ways of splitting the statistical distance over hyperedges into the statistical distance over the edges of swap graphs, we first define the following notion. We say that a binary tree \( T \) is a \( k \)-splitting tree if it has exactly \( k \) leaves. Thus, labeling every vertex with the number of leaves on the subtree rooted at that vertex ensures,
- the root of \( T \) is labeled with \( k \) and all other vertices are labeled with positive integers,
- the leaves are labeled with 1, and
- each non-leaf vertex satisfies the property that its label is the sum of the labels of its two children.

Note that, we will think of each non-leaf node with left and right children labeled as \( a \) and \( b \) as representing the swap graph from \( X(a) \) to \( X(b) \) for some simplicial complex \( X(\leq k) \). Let \( \text{Swap}(T, X) \) be the set of all such swap graphs over \( X \) finding representation in the splitting tree \( T \). Indeed the tree \( T \) used in the proof of Theorem VI.3 is just one special instance of a \( k \)-splitting tree.

Given a threshold parameter \( \tau \leq 1 \) and a set of normalized adjacency matrices \( A = \{A_{1}, \ldots, A_{n}\} \), we define the threshold rank of \( A \) as
\[ \text{rank}_{\geq \tau}(A) := \max_{A \in A} \text{rank}_{\geq \tau}(A), \]
where \( \text{rank}_{\geq \tau}(A) \) is denotes usual threshold rank of \( A \) as in Definition VII.1.

Now, we are ready to define the notion of a \( k \)-CSP instance being \( (T, \tau, r) \)-splittable as follows.

**Definition VII.2 ((\( T, \tau, r \))-splittablility).** A \( k \)-CSP instance \( \mathcal{I} \) with the constraint complex \( X(\leq k) \) is said to be \( (T, \tau, r) \)-splittable if \( T \) is a \( k \)-splitting tree and
\[ \text{rank}_{\geq \tau}(\text{Swap}(T, X)) \leq r. \]

If there exists some \( k \)-splitting tree \( T \) such that \( \mathcal{I} \) is \( (T, \tau, r) \)-splittable, the instance \( \mathcal{I} \) will be called a \( (\tau, r) \)-splittable instance.

Now, using this definition we can show that whenever \( \text{rank}_{\tau}(\mathcal{I}) \) is bounded for the appropriate choice of \( \tau \), after conditioning on a random partial assignment as in Algorithm VI.1 we will have small correlation over the faces \( a \in X(k) \), i.e.,
Theorem VII.3. Suppose a simplicial complex $X(\leq k)$ with $X(1) = \{n\}$ and an $L$-local PSD ensemble $Y = \{Y_1, \ldots, Y_n\}$ are given. There exists some universal constants $c_4 \geq 0$ and $C'' \geq 0$ satisfying the following: If $L \geq C'' \cdot (q^{4k} \cdot k^2 \cdot r/e^5)$, $\text{Supp}(Y_j) \leq q$ for all $j \in [n]$, and $\mathcal{I}$ is $(c_4 \cdot (e/(4k \cdot q^k))^2, r)$-splittable. Then, we have
\[
\mathbb{E}_{a \in \chi(k)} \left\| \{Y_a\} - \{Y_{a_1}\} \cdots \{Y_{a_k}\} \right\|_1 \leq \epsilon,
\]
where $Y'$ is as defined in Algorithm VI.1 on the input of $\{Y_1, \ldots, Y_n\}$ and $\Pi_k$.

It is important to note that the specific knowledge of the $k$-splitting tree $T$ that makes $\mathcal{I}$ ($T, \tau, r$)-splittable is only needed for the proof of Theorem VII.3. The conclusion of Theorem VII.3 can be used without the knowledge of the specific $k$-splitting tree $T$. Theorem VII.3 can be thought of an extension of Theorem VI.3 to the case where not necessarily every tree is good, and where we can bound the threshold rank instead of the spectral expansion.

This, will readily imply an algorithm

Corollary VII.4. Suppose $\mathcal{I}$ is a $q$-ary $k$-CSP instance whose constraint complex is $X(\leq k)$. There exists an absolute constant $C'' \geq 0$ and $c_4 \geq 0$ that satisfies the following: If $\mathcal{I}$ is $(c_4 \cdot (e/(4k \cdot q^k))^2, r)$-splittable, then there is an algorithm that runs in time $n^{O\left(\frac{2^{4k} \cdot q^k}{\epsilon^2}\right)}$ and is based on $(C'' / \epsilon^2)^{k^2}$-levels of SoS-hierarchy and Algorithm VI.1 that outputs a random assignment $\varphi : [n] \rightarrow [q]$ that in expectation ensures $\text{SAT}_3(\varphi) = \text{OPT}(\mathcal{I}) - \epsilon$.

We will need the more general version of Lemma VI.7, proved in [BRS11].

Lemma VII.5 (Lemma 5.4 from [BRS11]). \(^9\) Let $G = (V, E, \Pi_2)$ be a weighted graph, $\{Y_1, \ldots, Y_n\}$ a local PSD ensemble, where we have $\text{Supp}(Y_j) \leq q$ for every $i \in V$, and $q \geq 0$. If $\epsilon \geq 0$ is a lower bound on the expected statistical difference between independent and correlated sampling along the edges, i.e.,
\[
\epsilon \leq \mathbb{E}_{\{i,j\} \sim \Pi_2} \left\| \{Y_{ij}\} - \{Y_i\} \{Y_j\} \right\|_1.
\]
There exists absolute constants $c_3 \geq 0$ and $c_4 \geq 0$ that satisfy the following: Then, conditioning on a random vertex decreases the variances,
\[
\mathbb{E}_{i \sim \Pi_k} \mathbb{E}_{j \sim \Pi_k} \mathbb{E}_{\{Y_i, Y_j\} \sim \Pi_k} \mathbb{E} \left[ \text{Var} \left[ Y_i \mid Y_j \right] \right] \leq \mathbb{E}_{i \sim \Pi_k} \mathbb{E} \left[ \text{Var} \left[ Y_i \right] \right] - c_3 \cdot \epsilon^4 \cdot \frac{q^4 \cdot \text{rank}_{r \geq c_4^2/\epsilon^2}(G)}{256 \cdot k^4 \cdot q^{4k} \cdot r}.
\]

Since we will use this lemma, only with the swap graphs $G_{\ell_1, \ell_2}$ and $(L/k)$-local PSD ensemble $\{Y_a\} \in X$ obtained from the $L$-local PSD ensemble $\{Y_1, \ldots, Y_n\}$, for convenience we will write the corollary we will use more explicitly

Corollary VII.6. Let $\ell_1 \geq \ell_2 \geq 0$ satisfying $\ell_1 + \ell_2 \leq k$ be given parameters, and let $G_{\ell_1, \ell_2}$ be the swap graph defined for a $\gamma$-HDX $X(\leq k)$. Let $\{Y_a\} \in X$ be a local PSD ensemble; and suppose we have $\text{Supp}(Y_a) \leq q^k$ for every $a \in X(\ell_1) \cup X(\ell_2)$ for some $q \geq 0$. Suppose $\epsilon > 0$ satisfies
\[
\epsilon \leq \frac{4k}{\{a, b\} \in E(\ell_1, \ell_2)} \left\| \{Y_{a,b}\} - \{Y_a\} \{Y_b\} \right\|_1.
\]
There exists absolute constants $c_3 \geq 0$ and $c_5 \geq 0$ that satisfy the following:
If $\text{rank}_{r \geq c_5 \cdot (e/(4k \cdot q^k))^2}(G_{\ell_1, \ell_2}) \leq r$, then conditioning on a random face $a \sim \Pi_{\ell_1, \ell_2}$ decreases the variances, i.e.
\[
\mathbb{E}_{a, b \sim \Pi_{\ell_1, \ell_2}} \mathbb{E}_{\{Y_a\} \sim \Pi_k} \mathbb{E} \left[ \text{Var} \left[ Y_b \mid Y_a \right] \right] \leq \mathbb{E}_{a \sim \Pi_{\ell_1, \ell_2}} \mathbb{E} \left[ \text{Var} \left[ Y_b \right] \right] - c_5 \cdot \frac{\epsilon^4}{256 \cdot k^4 \cdot q^{4k} \cdot r}.
\]

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\(^9\)The parameters we get differ from those of [BRS11]. The derivation of our parameters can be found in the appendix of the full version of this paper [AJT19].


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