Towards Strong Nonapproximability Results in the Lovasz-Schrijver Hierarchy

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ABSTRACT

Lovász and Schrijver described a generic method of tightening the LP and SDP relaxation for any 0-1 optimization problem. These tightened relaxations were the basis of several celebrated approximation algorithms (such as for MAX-CUT, MAX-3SAT, and SPARSEST CUT).

We prove strong inapproximability results in this model for well-known problems such as MAX-3SAT, HYPERGRAPH VERTEX COVER and SET COVER. We show that the relaxations produced by as many as $\Omega(n)$ rounds of the LS_+ procedure do not allow nontrivial approximation, thus ruling out the possibility that the LS_+ approach gives even slightly subexponential approximation algorithms for these problems.

We also point out why our results are somewhat incomparable to known inapproximability results proved using PCPs, and formalize several interesting open questions.

Categories and Subject Descriptors

F.1.3 [**Computation by Abstract Devices**]: Complexity Measures and Classes

General Terms

Algorithms, Theory

Keywords

Lovász-Schrijver matrix cuts, inapproximability, integrality gaps

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1. INTRODUCTION

The past decade has seen a dramatic improvement of our understanding of the approximation properties of many NP-hard optimization problems. Many new approximation algorithms were designed, especially using linear programming (LP) or semidefinite programming (SDP) relaxations. For many problems it was proved using probabilistically checkable proofs (PCPs) that these algorithms are the best possible polynomial-time algorithms unless $\mathbf{P} = \mathbf{NP}$.

This paper is motivated by two nagging facts about the state of the art. First, for some problems there is a large gap between the approximation ratio achieved by the best algorithms known and the approximation ratio ruled out by PCP-based results. For instance, the two ratios are 1.5 and 1.02 respectively for metric TSP, and 2 and 1.36... respectively for VERTEX COVER in graphs. Second, current PCP-based results do not rule out the existence of slightly subexponential-time approximation algorithms. This happens because they often use reductions that greatly increase the instance size. For example, the reduction from 3SAT to VERTEX COVER by Dinur and Safra [5] reduces 3SAT instances of size n to 1.36-approximation for VERTEX COVER on graphs of size n^C where C is an astronomical constant. Thus it does not rule out that 1.2-approximation to VERTEX COVER is possible in say $2^{n^{0.01}}$ time—an interesting possibility.

A recent paper of Arora, Bollobás, and Lovász [1] pointed out both these issues. It also suggested a concrete approach to study such questions: rule out good approximation algorithms that use "standard methods" of writing LP and SDP relaxations. After all, even though linear programming is P-complete, and hence in principle capable of representing arbitrary polynomial-time computations, current approximation algorithms are designed by writing LP relaxations in a certain way. A lowerbound for "large" families of relaxations could thus be viewed as a lowerbound for a restricted but important computational model (analogous to lowerbounds for restricted circuit classes or proof systems). Arora et al. proved that several families of relaxations cannot achieve an approximation ratio better than $2 - o(1)$ for VERTEX COVER. Related work of this nature is described below.

In this paper, we concentrate on lowerbounds for the approximation ratio of relaxations obtained by a general technique defined by Lovász and Schrijver [12]. (A related "lift and project" technique was also proposed by Sherali and

Adams [14].) Given an arbitrary relaxation of a 0-1 optimization problem, this gives two procedures LS and LS_+ for obtaining tighter and tighter relaxations for the integral polytope (formal definitions appear in Section 2). The relaxation obtained from r rounds is solvable in $n^{O(r)}$ time. Thus though $r = O(1)$ is the most interesting case, if we are also interested in subexponential algorithms then any value of r less than $n/\log n$ is also interesting. In general n rounds suffice to obtain the integral polytope, which achieves an approximation ratio 1. But it is conceivable that much fewer rounds suffice to get a very nontrivial approximation ratio. The well-known SDP relaxation in the Goemans-Williamson [9] 0.878-approximation to MAX-CUT is obtained by using one round of LS_+ on the standard LP relaxation, and the SDP relaxation with triangle inequalities used in the recent Arora-Rao-Vazirani [2] approximation for SPARSEST CUT is implied by three rounds of LS_+. (See Appendix B.)

We show that $\Omega(n)$ rounds of LS_+ do not suffice to achieve the following approximations for any $\epsilon > 0$: (i) approximating MAX-3SAT within a factor better than $7/8 - \epsilon$, (ii) approximating VERTEX COVER in rank-k hypergraphs within a factor better than $k - 1 - \epsilon$, (iii) approximating SET COVER within a factor better than $(1 - \epsilon) \ln n$.

Note that there are inapproximability results in the PCP setting where all the above factors appear [4, 10, 6, 13]. However, as mentioned already, those results use reductions that greatly blow up the instance size, and hence imply the above integrality gaps—under any complexity assumption at all—for only n^δ rounds (here $\delta > 0$ is some small constant) instead of for $\Omega(n)$ rounds. Moreover, for SET COVER the PCP results are even weaker: an integrality gap of $(1-\epsilon) \ln n$ for is implied only for $n^{o(1)}$ rounds [6]. (The PCP results for SET COVER in [13] do imply an $\Omega(\log n)$ gap for n^δ rounds for some constant $\delta > 0$; however the gap given is at most $c \log n$ for some small constant c.)

We further note a curious difference between the above lowerbounds for LS_+ and PCP-based inapproximability results. In the PCP world, once we have proved an inapproximability results for "canonical" problems such MAX-3SAT, we can use reductions to prove inapproximability results for many other problems. Proving integrality gaps via reductions in the LS world seems much harder if not impossible. In general this should not be surprising, since reductions use arbitrary polynomial-time computations, which may be outside the purview of the limited "reasoning" available in the LS_+ system (note that LS_+ is technically a proof system). What is more surprising to us is that even the simple gadget-based reductions typically encountered in NP-hardness proofs seem outside the purview of LS_+ reasoning. To give an example, approximating MAX-3SAT within a factor better than 7/8 is reducible via a textbook reduction (carried out entirely with local gadgets) to approximating VERTEX COVER in graphs within a factor better than 17/16. Nevertheless, we are unable to rule out $17/16 - \epsilon$ (or even weaker) approximations to VERTEX COVER in graphs, even though we have ruled out $7/8 - \epsilon$ approximations to MAX-3SAT. We describe the difficulties in Section 7.

This raises the tantalizing possibility that the familiar interrelationships among approximation problems that have emerged in the past decade breaks down when one considers subexponential time approximation algorithms. Only further work can resolve such issues, and we list some interesting open problems later. (We should mention that our lowerbound results were motivated by a failure to prove upperbounds.)

1.1 Comparison with related results.

Goemans and Tunçel [8] show that that LS_+ procedure cannot derive some simple inequalities in $\Omega(n)$ rounds, showing its limitations. Results relating to integrality gaps appear in more recent papers. Arora et al. [1] show that the integrality for VERTEX COVER remains $2 - \delta$ after $\Omega(\sqrt{\log n})$ rounds of LS. Feige and Krauthgamer [7] show a large gap remains for the maximum independent set problem after $\Omega(\log n)$ rounds of LS liftings.

Buresh-Oppenheim et al. [3] considered the problem of proving integrality gaps from the angle of propositional proof complexity. In the proof complexity setting, LS-type procedures can be viewed as deduction systems with a prescribed set of derivation rules. The axioms are the polytope constraints and the derivation rules give the inequalities implied by one round of LS_+ (for more details on the relation of refutations and LS_+ approximation algorithms see Section 7). Their paper [3] shows a linear lower bound on the number of LS_+ rounds needed to refute an unsatisfiable linear system for kSAT and kXOR-SAT when $k \geq 5$. In particular, for $k \geq 5$ they prove that a linear number of rounds of LS_+ is needed to obtain an integrality gap better than $(2^k - 1)/2^k - \epsilon$ for MAX-kSAT. The cases when $k \leq 4$ are left open.

With a couple of exceptions, lowerbounds in all prior papers use a simple "*protection lemma*" due to Lovász and Schrijver (see the discussion after Lemma 2.1 in Section 2). This lemma gives a sufficient condition for a point x outside the integral hull to survive one round of lifting. More generally, the protection lemma shows that such a point survives r rounds if some specific set T of points (given by the Lemma statement) survives $r - 1$ rounds. In the Lovász-Schrijver protection lemma, T is a set of $2n$ points that differ from x in exactly one coordinate. (The lone exceptions are two proofs in [12] and [1] where the set T is obtained by LP duality and not explicitly described.) The simple protection lemma fails to prove the integrality gaps that interest us, and we introduce a new protection lemma that may be of interest in subsequent work. One curious feature is that in order for this protection lemma to work for even one round, we need the underlying problem instance to have some *expansion* properties. In fact, expansion plays a key role in our lowerbounds.

Note that expansion also played a big role in Buresh-Oppenheim et al. [3], which was the inspiration for our work. Their techniques allow integrality gaps (albeit loose ones) to be shown for VERTEX COVER on rank-k hypergraphs for big values of k. However, their techniques seem to break down for $k = 3$ and $k = 4$—the most interesting cases after $k = 2$, which is of course VERTEX COVER on graphs. For related reasons their techniques also fail when trying to prove optimal integrality gaps for MAX-3SAT and MAX-4SAT. To prove our results we introduce, in addition to the above-mentioned new protection lemma, a subtle *expansion correction* strategy. We think that both ideas may prove useful in future work.

2. RELAXATIONS, TIGHTENINGS AND OUR METHODOLOGY

Using the VERTEX COVER problem (for graphs) we explain relaxations and how to tighten them using LS_+ lifting. The integer program (IP) characterization for a graph $G = (V, E)$ is: minimize $\sum_{i \in V} v_i$ such that $v_i + v_j \geq 1$ for all $\{i, j\} \in G$ in the graph, where $v_i \in \{0, 1\}$. The *integer hull* denoted I, is the convex hull of all solutions to this problem. The standard LP relaxation is to allow $0 \leq v_i \leq 1$. The value of the LP is no more than that of the IP. Let P be the convex hull of all solutions vectors in $[0, 1]^n$ to the LP. A linear relaxation is *tightened* by adding more and more constraints that also hold for the integral hull; in general this gives some polytope P' such that $I \subseteq P' \subseteq P$.

The quality of a linear relaxation is measured by the ratio $\frac{\text{optimum value over } I}{\text{optimum value over } P}$, usually called its *integrality gap*. For the VERTEX COVER relation, this ratio is 2. (Note: When designing approximation algorithms, one also needs some kind of *rounding algorithm* to convert fractional solutions to integer ones in polynomial time, but we ignore this aspect.)

Lovász and Schrijver [12] present a so-called "lift-and-project" technique for deriving tighter and tighter relaxations of a 0-1 integer program. The n dimensional relaxed polytope is lifted to n^2 dimensions, new constraints are introduced, and then projected back into the original space.

The notation for these LS liftings (sometimes also referred to as LS *matrix cuts*) uses homogenized inequalities. In particular, given a polytope $P \subseteq \mathbb{R}^n$ for a linear relaxation, let $Q \subseteq \mathbb{R}^{n+1}$ be the cone $\{\binom{a}{\vec{x}} : \vec{x}/a \in P\}$. For example, if P is the VERTEX COVER polytope, then $(x_0, x_1, \ldots, x_n) \in Q$ iff the edge constraints $x_i + x_j \geq x_0$ hold for all edges $\{x_i, x_j\}$ in the graph. Denote by $N^r(Q)$ and $N_+^r(Q)$ the feasible cone of all inequalities derivable in r rounds of the LS and LS_+ lifting procedure, respectively. Let $N^0(Q) = N_+^0(Q) = Q$. The rth round polytope is then obtained by projecting along the hyperplane $x_0 = 1$. We will often abuse notation and write $N_+^r(P)$ to indicate the polytope obtained after r rounds of LS_+ lifting. Lovász and Schrijver prove that if there exists a polynomial time separation oracle for P then one can optimize a linear function over $N^r(P)$ and $N_+^r(P)$ in time $n^{O(r)}$.

The following lemma from [12] characterizes the N and N_+ operators. (Note that in the lemma and the remainder of this paper we will index columns and rows of a matrix starting from 0 rather than 1.)

LEMMA 2.1. *Let Q be a cone as defined above. Then $y = \binom{1}{\vec{x}}$ is in $N(Q)$ iff there is a symmetric matrix $Y \in \mathbb{R}^{(n+1)\times(n+1)}$ such that:*

1. *$Ye_0 = diag(Y) = y$,*
2. *$Ye_i, Y(e_0 - e_i) \in Q$, for all $i = 1, \ldots, n$.*

Condition 2 can be equivalently stated as:

2'. *For each i such that $x_i = 0$, $Ye_i = 0$; for each i such that $x_i = 1$, $Ye_i = y$; Otherwise Ye_i/x_i and $Y(e_0 - e_i)/(1 - x_i)$ are both in P (i.e., the projection of Q along the hyperplane $x_0 = 1$).*

Finally, $y = \binom{1}{\vec{x}}$ is in $N_+(Q)$ iff in addition Y is positive semidefinite.

It can be verified from the definition that $N_+^{r+1}(Q) \subseteq N_+^r(Q)$. Notice, to prove that $y \in N_+^{r+1}(Q)$, we have to construct a specific matrix Y and prove that the $2n$ vectors defined in Lemma 2.1 are in $N_+^r(Q)$. Choosing such a Y gives what Buresh-Oppenheim et al. call a "protection lemma": a point survives one round of LS if the $2n$ vectors given by Y are in the previous polytope.

The simplest Y one could conceive of is $Y_{ij} = y_i y_j$ (this is trivially positive semidefinite); however, this matrix satisfies $diag(Y) = y$ only if y is a 0-1 vector. Indeed, this proves that all polytopes resulting from LS-type liftings contain the integral hull. The next simplest Y one could conceive is $Y = yy^T + \mathrm{Diag}(y - y^2)$, that is, the matrix that has $Y_{ij} = y_i y_j$ except along the diagonal where $Y_{ii} = y_i$. For $y \in [0, 1]^n$ this is clearly positive semidefinite, and indeed, this matrix was used in early results by Lovasz-Schrijver [12] and Goemans-Tuncel [8], and more recently, Buresh-Oppenheim et al. [3].

With this choice of Y, the vectors Ye_i/x_i and $Y(e_0 - e_i)/(1 - x_i)$ are obtained by changing *one* coordinate in y to a 0 or a 1. However, for MAX-3SAT and hypergraph VERTEX COVER, these vectors are not guaranteed to be in the polytope. Thus other than for the SET COVER problem, this simple protection lemma does not suffice for us.

Our response is to use a more complicated Y, such that most entries satisfy $Y_{ij} = y_i y_j$, but some don't. Then the $2n$ vectors generated above correspond to modifying Y in a small number of entries. (A similar idea occurred in [1], except the Y there was not explicit.) This is at the heart of our new protection lemmas for MAX-3SAT and hypergraph VERTEX COVER. To make this choice of Y work out, we need certain expansion requirements to be met.

With our "protection lemma" in hand, the lowerbound strategy will be as follows: Given our relaxed polytope P, we identify a point $w \in P$ for which the ratio between the integral optimum and the value of the objective function at w is large. We will then prove the lowerbound by showing that w survives many rounds of LS_+. We do this via a Prover-Adversary game where the Prover is trying to prove that $w \in N_+^r(P)$ and the Adversary's goal is to show the opposite. For the Adversary to win, it will suffice for him to exhibit a vector amongst the $2n$ vectors given by our "protection lemma" that is not in $N_+^{r-1}(P)$. He picks such a vector x and "challenges" the Prover to show it is in $N_+^{r-1}(P)$. Things continue this way, and the Prover loses if she cannot keep the game going for r steps. To keep the argument clean, we need to maintain the vector x in a nice form throughout the game. To this end, we borrow an idea from [3]: during each round, to prove that a particular point x is in a certain polytope, the Prover can also choose to express the point as a convex combination $\sum_j \rho_j z_j$ and claims that every $z_j \in N_+^{r-1}(P)$ (and consequently so is x). To counter this claim, the Adversary picks some z_j which he thinks is not in $N_+^{r-1}(P)$, and the game continues for that vector. We will show that if the constraints defining P satisfy certain expansion requirements, then for appropriate w, the Prover has a linear round strategy against any Adversary.

3. INCIDENCE GRAPHS OF CONSTRAINTS

Given a hypergraph $G = (V, E)$, let H_G be the bipartite incidence graph on $E \times V$ where each each hyperedge is connected to the vertices it contains. We will often use the notion of *expansion* in a bipartite graph.

DEFINITION 3.1. *A bipartite graph $G = (V_1, V_2, E)$ is an*

(r,c)-expander *if every subset $S \subseteq V_1$, $|S| \leq r$, satisfies $|\Gamma(S)| \geq c|S|$, where $\Gamma(S)$ is the set of neighbours of S in V_2.*

Throughout this paper we will deal with constraints of the form $\sum_i v_i^{\epsilon_i} \geq 1$ where $v_i^{\epsilon_i}$ represents v_i if $\epsilon_i = 1$ and $v_i^{\epsilon_i}$ represents $1 - v_i$ if $\epsilon_i = 0$. Say that a variable $v_i^{\epsilon_i}$ occurs *negated* in a constraint if $\epsilon_i = 0$. Let C be a set of such constraints on a set V of n variables. Given an assignment vector $x \in [0,1]^n$ for V, we define $C(x)$ to be the set of constraints obtained from C as follows: (a) If $x_i = 0$, remove all constraints containing v_i negated; (b) if $x_i = 1$, remove all constraints containing v_i unnegated; and (c) remove all variables set to 0-1 by x from the remaining constraints. Intuitively, $C(x)$ is the set of simplified constraints in C not trivially satisfied by x. In particular, if x satisfies $C(x)$, then x satisfies C.

Let $V(x)$ be the set of those variables in V not set to 0-1 by x and let $H(x)$ be the bipartite incidence graph on $C(x) \times V(x)$; that is, for each constraint in $C(x)$ there is an edge to every variable it contains. Let H be the incidence graph on $C \times V$. We will say that $C(x)$ is an *(r,c)-expander* if $H(x)$ is an (r,c)-expander. We will say that the *arity* of a constraint is t if it has t neighbours in $H(x)$. For a subset $S \subseteq C(x)$ of constraints, denote the variables in S (i.e., the neighbours of S in $H(x)$) by $\Gamma(S)$.

Usually $C(x)$ will have some expansion property, and in particular will be at least a $(2, k-1-\epsilon)$-expander. Then all constraints in $C(x)$ will have arity at least $k-1$. Moreover, whenever $C(x)$ is an expander, constraints of arity $k-1$ will enjoy some special properties of which we will take advantage. For a vector $x \in \mathbb{R}^n$, let $R(x)$ denote the set of all indices to non-integral coordinates of x.

Definition 3.2. *Let $0 < \epsilon < 1/2$ and $x \in \{0, \frac{1}{k-1}, 1\}^n$ and suppose $C(x)$ is a $(2, k-1-\epsilon)$-expander. Two indices $i, j \in R(x)$ are* $C(x)$-equivalent *(written $i \sim_{C(x)} j$) if there is a constraint in $C(x)$ of arity $k-1$ containing v_i and v_j. Let $E(x) \subseteq R(x)$ contain all indices $i \in R(x)$ for which there exists $j \in R(x), j \neq i$ such that $i \sim_{C(x)} j$.*

The following proposition will be used repeatedly in our lower bound proofs and follows easily from expansion.

Proposition 3.3. *Let $0 < \epsilon < 1/2$ and $x \in \{0, \frac{1}{k-1}, 1\}^n$ and suppose $C(x)$ is $(2, k-1-\epsilon)$-expanding.*

Fact 1. A given variable can only occur in one arity $k-1$ constraint in $C(x)$. Hence, each $C(x)$-equivalence class has exactly $k-1$ elements.

Fact 2. Any given constraint in $C(x)$ (other than the arity $k-1$ constraint defining the equivalence) can contain at most one variable from any given $C(x)$-equivalence class.

4. LOWERBOUNDS FOR HYPERGRAPH VERTEX COVER

Let $G = (V, E)$, $E \subseteq V^k$, be a k-uniform hypergraph. The vertex cover problem for G is to find the smallest subset $S \subseteq V$ such that all hyperedges in G contain at least one element from S. The problem is expressed by the following integer program where variable $v_i \in \{0,1\}$ corresponds to vertex i in the graph:

$$\min \sum_{v_i \in V} v_i$$

$$\sum_{j=1}^{k} v_j \geq 1, \quad \forall (v_1, \ldots, v_k) \in E.$$

Let us relax to $0 \leq v_i \leq 1$. Let $\mathrm{VC}(G)$ then be the polytope consisting of all points $w \in \mathbb{R}^n$ satisfying the relaxed constraints, that is, $w \in \mathbb{R}^n$ is in $\mathrm{VC}(G)$ if setting $v_i = w_i$ for all i results in all relaxed constraints being satisfied. It is easy to see for the complete k-uniform hypergraph on n vertices the optimal value of the integer program is $n-k+1$ while the optimum value of the relaxed linear program is n/k. Therefore, the integrality gap between the integer and linear programs is at least $k - o(1)$.

We prove that even after a linear number of rounds of LS_+ tightenings of $\mathrm{VC}(G)$ there still exists some graph for which the integrality gap is $k - 1 - o(1)$.

Theorem 4.1. *Let $k \geq 3$. For all $\alpha > 0$ there exist $\gamma > 0$ and a k-uniform hypergraph G such that the integrality gap of any γn round LS_+ relaxation of $\mathrm{VC}(G)$ is at least $(k-1)(1-\alpha)$.*

Given $G = (V, E)$, let C_G be the set of hyperedge constraints defining $\mathrm{VC}(G)$. Since the underlying graph G will usually be clear, we omit the subscript unless extra precision is needed. In this section we will always have $x \in \{0, \frac{1}{k-1}, 1\}^n$ and $C(x)$ will be at least a $(2, k-1-\epsilon)$-expander. Then all constraints in $C(x)$ will have arity at least $k-1$ and the following will hold:

Proposition 4.2. *Let $0 < \epsilon < 1/2$, and $x \in \{0, \frac{1}{k-1}, 1\}^n$, and suppose that $C(x)$ is $(2, k-1-\epsilon)$-expanding. Then $x \in \mathrm{VC}(G)$.*

We now define the vectors that will appear in our "Protection Lemma" for vertex cover. For the remainder of this section we will always assume $0 < \epsilon < 1/2$.

Definition 4.3. *Given $x \in [0,1]^n$, for all $i \in R(x)$ and all $a \in \{0,1\}$ define $x^{(i,a)}$ to be identical to x except that $x_i^{(i,a)} = a$.*

Definition 4.4. *Let $x \in \{0, \frac{1}{k-1}, 1\}^n$, and suppose $C(x)$ is $(2, k-1-\epsilon)$-expanding. For all $i \in E(x)$ define $x^{[i]}$ to be identical to x except that $x_i^{[i]} = 1$ and $x_j^{[i]} = 0$ for all $j \sim_{C(x)} i$. Let the set $T_x \subseteq \{0, \frac{1}{k-1}, 1\}^n$ equal the union $\{x^{[i]} : i \in E(x)\} \cup \{x^{(i,a)} : i \in R(x) \backslash E(x), a \in \{0,1\}\}$.*

Lemma 4.5. *Let $x \in \{0, \frac{1}{k-1}, 1\}^n$, and suppose $C(x)$ is $(2, k-1-\epsilon)$-expanding. Then $R(x) \subseteq \mathrm{VC}(G)$. Moreover, for all $y \in T_x$, each constraint in $C(y)$ has arity at least $k-1$.*

Proof. There are two types of points in T_x: (1) $x^{(i,a)}$ for $i \in R(x) \backslash E(x)$ and (2) $x^{[i]}$ for $i \in E(x)$. Consider a point $x^{(i,a)}$ in T_x where $i \in R(x) \backslash E(x)$. In this case, v_i does not belong to any arity $k-1$ constraint in $C(x)$. Hence, every constraint in $C(x^{(i,a)})$ has arity at least $k-1$ in $C(x^{(i,a)})$, and is therefore satisfied by $x^{(i,a)}$.

Now consider a point $x^{[i]}$ in T_x such that $i \in E(x)$. By Fact 2 on equivalences and the definition of $x^{[i]}$, every constraint in $C(x)$ that had arity k in $C(x)$ has arity at least $k-1$ in $C(x^{(i,a)})$, and hence is satisfied by $x^{(i,a)}$. By Fact 1 on equivalences, the only arity $k-1$ constraint in $C(x)$ for which the values of any of its variables changes under $x^{[i]}$ is the unique arity $k-1$ constraint containing v_i. But such a constraint is satisfied by $x^{[i]}$ since v_i is set to 1 in $x^{[i]}$. □

LEMMA 4.6. ("PROTECTION LEMMA" FOR HYPERGRAPH VC) *Suppose $C(x)$ is $(2, k-1-\epsilon)$-expanding where $x \in \{0, \frac{1}{k-1}, 1\}^n$. Suppose moreover that $T_x \subseteq N_+^m(\mathrm{VC}(G))$. Then $x \in N_+^{m+1}(\mathrm{VC}(G))$.*

PROOF. Let $y = \binom{1}{x}$. The proof uses Lemma 2.1 and the following choice of an $(n+1)\times(n+1)$ positive semidefinite symmetric matrix Y that is $yy^T + \mathrm{Diag}(y - y^2)$ except that $Y_{ij} = 0$ whenever $i \sim_{C(x)} j$. Note that Y is symmetric and that $Ye_0 = diag(Y) = y$. Moreover, by Proposition 4.7 below, Y is positive semi-definite. (This uses the expansion properties of $C(x)$.) So by Lemma 2.1, to show that $x \in N_+^{m+1}(\mathrm{VC}(G))$ it remains only to show that for all $i \in R(x)$, Ye_i/x_i and $Y(e_0 - e_i)/(1-x_i)$ are in $N_+^m(\mathrm{VC}(G))$.

For $i \in R(x)\backslash E(x)$, $Ye_i/x_i = \binom{1}{x^{(i,1)}}$ and $Y(e_0 - e_i)/(1 - x_i) = \binom{1}{x^{(i,0)}}$ and hence are both in $T_x \subseteq N_+^m(\mathrm{VC}(G))$. For $i \in E(x)$, $Ye_i/x_i = \binom{1}{x^{[i]}}$ which is in $T_x \subseteq N_+^m(\mathrm{VC}(G))$. Finally, for $i \in E(x)$, $Y(e_0 - e_i)/(1-x_i) = \binom{1}{z}$ where

$$z = \frac{1}{k-2} \sum_{j \sim_{C(x)} i,\ j \neq i} x^{[j]}.$$

In particular, $Y(e_0 - e_i)/(1 - x_i)$ is in the convex hull of $T_x \subseteq N_+^m(\mathrm{VC}(G))$, and hence is also in $N_+^m(\mathrm{VC}(G))$. □

PROPOSITION 4.7. *The matrix Y defined in the proof of Lemma 4.6 is positive semidefinite (PSD).*

PROOF. By Fact 1 on $C(x)$-equivalences, there exist disjoint sets $I_1, \ldots, I_t$ of indices such that (a) $|I_j| = k-1$ for all $j \in [t]$, (b) all indices belonging to an equivalence are in one of the I_j, and (c) for each $j \in [t]$ all indices in I_j are mutually equivalent. Then,

$$Y = yy^T + \mathrm{Diag}(y - y^2) + \sum_{j\in[t]} \left(\mathrm{Diag}(y_{I_j}^2) - y_{I_j} y_{I_j}^T\right),$$

where y_I equals y but is zero outside I.

To show Y is PSD, we show that $z^T Y z \geq 0$ for all $z \in \mathbb{R}^{n+1}$. Note that $z^T(yy^T)z = (y^T z)^2 \geq 0$ for all $z \in \mathbb{R}^{n+1}$. Moreover, $\mathrm{Diag}(w)$ is PSD for any w such that $w_j \geq 0$ for all j. Hence, since the sum of PSD matrices is PSD, to show that Y is PSD it suffices to show for each I_j that the following quantity is non-negative:

$$\begin{aligned} z^T(\mathrm{Diag}(y_{I_j} - y_{I_j}^2) + \mathrm{Diag}(y_{I_j}^2) - y_{I_j} y_{I_j}^T)z \\ = z^T(\mathrm{Diag}(y_{I_j}) - y_{I_j} y_{I_j}^T)z. \end{aligned}$$

Since the argument is identical for all I_j we drop the subscript j and assume $I = [k-1]$. The above then simplifies to $\sum_{i\in[k-1]}(z_i^2 x_i) - (\sum_{i\in[k-1]} z_i x_i)^2$. Since $x_i = \frac{1}{k-1}$ for all indices in an equivalence, this further simplifies to

$$\frac{1}{k-1}\sum_{i\in[k-1]} z_i^2 - \frac{1}{(k-1)^2}\left(\sum_{i\in[k-1]} z_i\right)^2,$$

which is non-negative since $\sum_{i\in[\ell]} a_i^2 \geq \frac{1}{\ell}(\sum_{i\in[\ell]} a_i)^2$. □

4.1 Proof of Theorem 4.1

Let $\alpha, \epsilon > 0$ be arbitrarily small. By Lemma A.1 in the Appendix, there are constants $\beta, \delta > 0$ such that a rank k hypergraph G exists with n vertices and βn edges such that the bipartite graph H_G is a $(\delta n, k-1-\epsilon)$-expander, and every vertex cover of G has size at least $(1-\alpha)n$. We show that the vector $w = (\frac{1}{k-1}, \ldots, \frac{1}{k-1})$, corresponding to a fractional vertex cover of "size" $n/(k-1)$, is in $N_+^r(\mathrm{VC}(G))$ where $r = \frac{\epsilon\delta n}{k-1}$. It follows that this many rounds of LS_+ cannot reduce the integrality gap below $(k-1)(1-\alpha)$, and Theorem 4.1 then follows for $\gamma = \frac{\epsilon\delta}{k-1}$. Note that H_G is isomorphic to $H(w)$, and hence, $C(w)$ is $(\delta n, k-1-\epsilon)$-expanding. This will be crucial for the lower bound.

The lowerbound will follow from a Prover-Adversary game of the type discussed in Section 2. We describe the game more formally. In round i there is a parameter $\ell_i \geq 2$ and a current point $x \in \{0, \frac{1}{k-1}, 1\}^n$. For $i = 0$, x is some initial point $w' \in \{0, \frac{1}{k-1}, 1\}^n$. At the beginning of round i, $C(x)$ will be an $(\ell_i, k-1-2\epsilon)$-expander. In round i the following two moves are made.

1. **Adversary Move:** The Adversary selects z from T_x.
2. **Expansion Correction:** The Prover constructs a set $Y \subseteq \{0, \frac{1}{k-1}, 1\}^n$ such that (1) z is in the convex hull of Y, and (2) for all $y \in Y$, $C(y)$ is an $(\ell_{i+1}, k-1-2\epsilon)$-expander where $\ell_{i+1} \leq \ell_i$. The Adversary selects one point $y \in Y$ to be the new x.

The game ends when $\ell_{i+1} \leq 1$.

Intuitively, the Adversary fixes more and more fractional-valued coordinates in the initial point w' to 0-1 values by replacing the current point x with a point z from T_x (note that once a coordinate is set to 0-1 it remains fixed). The Prover wants this to continue for as long as possible but may run into trouble if $C(z)$ is no longer a good expander. The Prover therefore does Expansion Correction to obtain a new x for which $C(x)$ is a good expander. The next lemma shows that a good Prover strategy implies w' has high rank.

LEMMA 4.8. *Suppose $w' \in \{0, \frac{1}{k-1}, 1\}^n$ is in $\mathrm{VC}(G)$. If for w' the Prover has an m round strategy against any adversary, then $w' \in N_+^m(\mathrm{VC}(G))$.*

PROOF. By induction on m. Since $w' \in \mathrm{VC}(G)$ by assumption, case $m = 0$ follows. So suppose the claim is true for m and that the Prover has an $m+1$ round strategy against any adversary. Consider the first round of the game and suppose the Adversary picks $z \in T_x$. Let Y be the set subsequently constructed by the Prover in the Expansion Correction move. Since the game runs for m more rounds regardless of which $y \in Y$ the Adversary chooses, $Y \subseteq N_+^m(\mathrm{VC}(G))$ by induction, and $z \in N_+^m(\mathrm{VC}(G))$ by convexity. This holds no matter which $z \in T_x$ the Adversary chooses, and so $T_x \subseteq N_+^m(\mathrm{VC}(G))$. Lemma 4.6 then implies $w' \in N_+^{m+1}(\mathrm{VC}(G))$. □

So to prove $w = (\frac{1}{k-1}, \ldots, \frac{1}{k-1}) \in N_+^r(\mathrm{VC}(G))$ and complete the proof of Theorem 4.1, it suffices to describe an r round strategy for the Prover when the initial point is w.

LEMMA 4.9. *If $C(w)$ is a $(\delta n, k-1-\epsilon)$-expander, then the Prover has an r round strategy against any Adversary, where $r = \frac{\epsilon\delta n}{k-1}$.*

PROOF. We start the game with $x = w$. Proposition 4.2 implies $w \in \mathrm{VC}(G)$. In round i of the strategy the parameter ℓ_i will be defined such that for the current point x the Prover can ensure $C(x)$ is an $(\ell_i, k-1-2\epsilon)$-expander. At the start, $\ell_1 = \delta n$.

The strategy will work as follows: The two moves made in each round of the game remove more and more variable vertices from the incidence graph $H(w)$ on $C(w) \times V(w)$. In each round at most $k-1$ variable vertices are removed from $H(w)$ by the Adversary choosing $z \in T_x$. As for the Expansion Correction move, the Prover will "correct" expansion in round i by identifying a maximal non-expanding set S_i of constraints of size at most ℓ_i and removing it and its neighbours from $H(x)$. Letting $\ell_{i+1} = \ell_i - |S_i|$, the resulting graph would then be an $(\ell_{i+1}, k-1-2\epsilon)$-expander. The Prover removes these constraints in S_i by having the assignments Y be 0-1 on $\Gamma(S_i)$ and equal to x outside $\Gamma(S_i)$. If $\ell_{i+1} \le 1$, the game ends; otherwise, the game continues. The claim is that such a strategy results in at least r rounds: Suppose the strategy lasts m rounds and consider $S = \cup S_i$. Then

$$|S| = \sum_{i=1}^{m} |S_i| = \sum_{i=1}^{m} \ell_i - \ell_{i+1} = \delta n - \ell_{m+1}.$$

By expansion, S had at least $(k-1-\epsilon)|S|$ neighbours in $H(w)$. However, at the end of the game, S has no neighbours. Expansion Correction removes at most $(k-1-2\epsilon)|S|$ neighbours. Since the Adversary Move removes at most $k-1$ neighbours per round, there must be at least $\epsilon\delta n/(k-1)$ rounds.

It remains to describe the Prover's strategy in round i in detail: If $\ell_i \le 1$ the game ends. Otherwise, Proposition 4.2 implies $x \in \mathrm{VC}(G)$ and the Adversary selects $z \in T_x$. Note that Lemma 4.5 implies $z \in \mathrm{VC}(G)$ and that every constraint in $C(z)$ has arity at least $k-1$. We now describe how the Prover constructs the set Y for Expansion Correction:

1. If $C(z)$ is an $(\ell_i, k-1-2\epsilon)$-expander, the Prover takes $Y = \{z\}$ and sets $S_i = \emptyset$.

2. Otherwise, let $S_i \subseteq C(z)$, $|S_i| \le \ell_i$, be a maximal subset of constraints with expansion less than $k-1-2\epsilon$ in $C(z)$. If $|S_i| \ge \ell_i - 1$, i.e., $\ell_{i+1} \le 1$, the game ends, and we let the final x be the same as z except it is 0 on $\Gamma(S_i)$.

3. Otherwise we claim that for all subsets $S' \subseteq S_i$ of constraints in $C(z)$, $|\Gamma(S')| > (k-2)|S'|$: Either the Adversary chose some $x^{(j,a)} \in T_x$ where j is not in any $C(x)$-equivalence class (in which case S' has expansion greater than $k-2$ in $C(z)$), or it chose $x^{[j]}$ where v_j occurs in some arity $k-1$ constraint $\phi \in C(x)$. Suppose ϕ shares t variables with $\Gamma(S')$. By expansion of $C(x)$,

$$\begin{aligned} |\Gamma(S')| &= |\Gamma(S' \cup \{\phi\})| - k + 1 + t \\ &\ge (k-1-2\epsilon)|S'| + t - 2\epsilon. \end{aligned}$$

   Since S' has exactly t fewer neighbours in $C(z)$ than in $C(x)$, the claim follows.

4. Let $S_i = (e_1, \ldots, e_t)$. By Lemma A.3 in the appendix there exists a mapping $\eta : S \to \mathcal{P}(\Gamma(S))$ such that (1) for all $i \in [t]$, $|\eta(e_i)| = k-1$, and (2) for all $i \in [t]$, $|\eta(e_i) \setminus \bigcup_{j<i} \eta(e_j)| \ge k-2$. We construct $k-1$ assignments $y^1, \ldots, y^{k-1}$ inductively according to the ordering $e_1, \ldots, e_t$. At the beginning all the y^j equal x outside $C(z)$ and are undefined on $\Gamma(S_i)$. Assume that at step t the values y_i^j for all $j \in [k-1]$ and for all i such that $v_i \in \bigcup_{i'<t} \eta(e_{i'})$ have been defined so that the constructed partial assignments satisfy all $e_{i'}$, $i' < t$, and the assigned values $y_i^1, \ldots, y_i^{k-1}$ contain exactly one 1 for each i. Consider e_t. Choose $k-2$ vertices $v_{i_1}, \ldots, v_{i_{k-2}} \in \eta(e_t)$ such that the values $y_{i_1}^j, \ldots, y_{i_{k-2}}^j$ are undefined for all $j \in [k-1]$ (these vertices exist by definition of η). Let $v_{i_{k-1}}$ be the other vertex in $\eta(e_{t+1})$. If the corresponding variables $y_{i_{k-1}}^1, \ldots, y_{i_{k-1}}^{k-1}$ are undefined then set the last of these variables to one and the rest to zeros. Assume without loss of generality that $y_{i_{k-1}}^{k-1} = 1$. For all other vertices in $\eta(e_{t+1})$ we set $y_{i_j}^j = 1$ and the rest to zeros. We have extended our partial assignments for $\eta(e_t)$ in a way that satisfies the induction hypothesis. At the the end, $y^1, \ldots, y^{k-1}$ each satisfy S_i and z is their average. Let $Y = \{y^1, \ldots, y^{k-1}\}$.

□

5. LOWERBOUNDS FOR MAX-3SAT

The arguments used to prove Theorem 4.1 can be adapted to prove integrality gaps for MAX-3SAT. Given a 3-CNF formula ϕ, we convert its clauses to inequalities in the obvious way, i.e., $x_1 \vee x_2 \vee \neg x_3$ becomes $x_1 + x_2 + (1 - x_3) \ge 1$. Let C_ϕ be the set of such inequalities corresponding to ϕ. Note that the 0-1 solutions to these inequalities correspond exactly to the satisfying assignments for ϕ. Relaxing to $x_i \in [0,1]$ yields a polytope $\mathrm{SAT}(\phi)$ whose integral points are solutions for ϕ.

THEOREM 5.1. *For any constant $\alpha > 0$, there exist constants $\beta, \gamma > 0$ such that if ϕ is a random βn clause 3-CNF formula on n variables, then the integrality gap of any γn round LS_+ relaxation of $\mathrm{SAT}(\phi)$ is at least $\frac{8}{7} - \alpha$ with high probability.*

Let $w = (\frac{1}{2}, \ldots, \frac{1}{2})$ and note that $w \in \mathrm{SAT}(\phi)$ for any formula ϕ. The proof of the above theorem will rely on the following lemma:

LEMMA 5.2. *Let $0 < \epsilon < \frac{1}{2}$, and suppose $C_\phi(w)$ is a $(\delta n, 2-\epsilon)$-expander. Then $w \in N_+^{\epsilon\delta n/2}(\mathrm{SAT}(\phi))$.*

PROOF OF THEOREM 5.1. It is well-known that for all $\alpha, \epsilon > 0$, there exist constants $\beta, \delta > 0$ such that if we pick a random 3-CNF ϕ with βn clauses, then with high probability (1) no boolean assignment satisfies more than a $\frac{7}{8} + \alpha$ fraction of the clauses in ϕ and (2) C_ϕ is a $(\delta n, 2-\epsilon)$-expander. On the other hand, Lemma 5.2 says that w, which satisfies *all* clauses in ϕ, is in $N_+^r(\mathrm{SAT}(\phi))$ where $r = \epsilon\delta n/2$. □

The proof of Lemma 5.2 is identical to that of Lemma 4.9 with the only changes being in (1) the "protection lemma" (Lemma 4.6) which must be altered to take into account the negated variables now appearing in the constraints; and (2) in the game, where the Prover's Expansion Correction strategy also has to accommodate negated variables. We finish this section therefore by stating and proving the new protection lemma used in the proof of Lemma 5.2 and by sketching a proof of the new Expansion Correction strategy used in the proof of Lemma 5.2.

DEFINITION 5.3. *Suppose $x \in \frac{1}{2}\mathbb{Z}^n$ and let $i \in R(x), a \in \{0,1\}$. Let $x^{[i,a]} \in \frac{1}{2}\mathbb{Z}^n$ be identical to x except*

1. *$x_i^{[i,a]} = a$, and*
2. *if there exists an arity 2 constraint $v_i^{\epsilon_i} + v_j^{\epsilon_j} \geq 1$ in $C(x)$, then $x_j^{[i,a]} = 1 - a$ if $\epsilon_i = \epsilon_j$ and $x_j^{[i,a]} = a$ if $\epsilon_i \neq \epsilon_j$.*

The key observation is that if $C(x)$ is $(2, 2-\epsilon)$-expanding, then for all $i \in R(x)$ and all $a \in \{0,1\}$, each constraint in $C(x^{[i,a]})$ has arity at least 2 and hence $x^{[i,a]} \in \mathrm{SAT}(\phi)$. Let $T_x = \{x^{[i,a]} : i \in R(x), a \in \{0,1\}\}$.

LEMMA 5.4. ("PROTECTION LEMMA" FOR MAX-3SAT) *Let $\epsilon > 0$ be an arbitrarily small constant and suppose $C(x)$ is $(2, 2-\epsilon)$-expanding where $x \in \frac{1}{2}\mathbb{Z}^n$. Suppose moreover that $T_x \subseteq N_+^m(\mathrm{SAT}(\phi))$. Then $x \in N_+^{m+1}(\mathrm{SAT}(\phi))$.*

PROOF. Let $y = \binom{1}{x}$. The proof uses Lemma 2.1 and the following choice of an $(n+1) \times (n+1)$ positive semidefinite matrix Y that is $yy^T + \mathrm{Diag}(y - y^2)$ except that if $x_i^{\epsilon_i} + x_j^{\epsilon_j} \geq 1$ is a constraint in $C(x)$, then $Y_{ij} = 0$ if $\epsilon_i = \epsilon_j$ and $Y_{ij} = \frac{1}{2}$ if $\epsilon_i \neq \epsilon_j$. Note that Y is symmetric and that $Ye_0 = diag(Y) = y$. Moreover, by Proposition 5.5 below it follows that Y is positive semidefinite. Finally, for all $i \in R(x)$, $Ye_i/x_i = \binom{1}{x^{[i,1]}}$ and $Y(e_0 - x_i)/(1-x_i) = \binom{1}{x^{[i,0]}}$. In particular, these vectors are in $N_+^m(\mathrm{SAT}(\phi))$ since their projections along the hyperplane $x_0 = 1$ are in T_x. $\square$

PROPOSITION 5.5. *The matrix Y defined in the proof of Lemma 5.4 is positive semidefinite (PSD).*

PROOF. Let $I \subseteq \{0, 1, \ldots, n\}$ be the set of indices not in any $C(x)$-equivalence. For all $i, j \in \{1, \ldots, n\}$, define $(n+1) \times (n+1)$ matrices $A^{(i,j)}$ and $B^{(i,j)}$ that are 0 everywhere except $A_{ii}^{(i,j)} = A_{jj}^{(i,j)} = 1/4$, $A_{ij}^{(i,j)} = A_{ji}^{(i,j)} = -1/4$, and $B_{ii}^{(i,j)} = B_{jj}^{(i,j)} = B_{i,j}^{(i,j)} = B_{ji}^{(i,j)} = 1/4$. Note that $A^{(i,j)}$ and $B^{(i,j)}$ are both PSD. Finally, let

$$C_1 = \{(i,j) : v_i^{\epsilon_i} + v_j^{\epsilon_j} \geq 1 \in C(x) \text{ and } \epsilon_i = \epsilon_j\},$$
$$C_2 = \{(i,j) : v_i^{\epsilon_i} + v_j^{\epsilon_j} \geq 1 \in C(x) \text{ and } \epsilon_i \neq \epsilon_j\}.$$

Since $C(x)$-equivalence classes are disjoint, it follows that each $k \in \{0, 1, \ldots, n\}$ is either in I or appears in exactly one pair from $C_1 \cup C_2$. Hence, by definition of Y,

$$Y = yy^T + \mathrm{Diag}(y_I - y_I^2) + \sum_{(i,j) \in C_1} A^{(i,j)} + \sum_{(i,j) \in C_2} B^{(i,j)}.$$

(Here y_I is the vector equal to y on the coordinates indexed by I but zero everywhere else.) Each of the terms in the above sum is PSD and hence, so is Y. $\square$

We now sketch how the Expansion Correction Strategy is altered. The overall argument goes the same way using Lemma A.3 with the only difference being that for $v_i \in \eta(e_t)$, the y_i^j, $j \in \{1, 2\}$, are set according to the signs the variables have in clause e_t so as to satisfy e_t.

6. LOWERBOUNDS FOR SET COVER

An instance of SET COVER consists of a tuple (S, C) where C is a collection of n subsets of a finite set S of size m. The objective is to find a minimum size subset $C' \subseteq C$ such that each element of S is in some set in C'. If for each set $S_i \in C$ we have a variable x_i indicating whether or not set S_i is included in the set cover, then the SET COVER problem is expressed by the following integer program:

$$\min \sum_{i=1}^{n} x_i$$
$$\sum_{i : j \in S_i} x_i \geq 1, \quad \forall j \in [m].$$

The relaxed SET COVER polytope $\mathrm{MSC}(S, C)$ is the polytope defined by the above constraints but where we allow $0 \leq x_i \leq 1$. Note now that if $G = (V, E)$ is a k-uniform hypergraph, and we let $S = E$ and $C = \{S_v\}_{v \in V}$ where $S_v = \{e \in E : v \in e\}$, then $\mathrm{MSC}(S, C)$ is identical to $\mathrm{VC}(G)$. Hence, integrality gaps for the hypergraph VC polytope yield integrality gaps for MSC.

Theorem 4.1 can therefore be used to obtain integrality gaps for LS_+ tightenings of the SET COVER polytope (in fact an earlier version of this paper did just that). However, stronger results can be obtained for SET COVER by using an argument specifically tailored for hypergraphs with edges of size $\Theta(\log n)$—this is what we do next.

Fix $\epsilon, \delta, \gamma > 0$ such that $\epsilon - \delta > 0$. By Lemma A.2 in the appendix, there exists an $(\epsilon - \delta)n$-uniform hypergraph $G = (V, E)$ on n vertices with n edges such that the minimum vertex cover is at least $\log_{1+\epsilon} n$. Consider the hyperedge constraints C_G defining $\mathrm{VC}(G)$. Let w be the all-$\frac{1+\gamma}{(\epsilon-\delta)n}$ point and note that w is in $\mathrm{VC}(G)$. Moreover, at least $\lfloor \frac{\gamma(\epsilon-\delta)n}{1+\gamma} \rfloor$ coordinates of w can be changed to 0 or 1 with the resulting point still satisfying all the constraints C_G.

Let us recall the simple protection lemma proved by Goemans and Tunçel [8] and described in section 2: For a relaxed polytope P, a point x is in $N_+(P)$ if for all $i \in R(x)$ and all $a \in \{0,1\}$, $x^{(i,a)}$ is in P. That is, x is in $N_+(P)$ if whenever we change exactly one coordinate of x to 0 or 1, the resulting point is in P. So by induction, this simple protection lemma together with the observation about w in the previous paragraph prove the following:

LEMMA 6.1. *The point w is in $N^r(\mathrm{VC}(G))$ where $r = \lfloor \frac{\gamma(\epsilon-\delta)n}{1+\gamma} \rfloor$.*

Finally note that since the minimum vertex cover for G has size $\log_{1+\epsilon} n$, the integrality gap for w is $\frac{(\epsilon-\delta)\ln n}{(1+\gamma)\ln(1+\epsilon)}$ which approaches $\ln n$ from below as $\epsilon, \delta, \gamma \to 0$. Thus we have proved the following gap for SET COVER:

THEOREM 6.2. *For all $\epsilon > 0$, there exists $\delta > 0$ and an instance (S, C), $|S| = n$, of SET COVER for which the integrality gap of the δn round LS_+ relaxation of $\mathrm{MSC}(S, C)$ is $(1 - \epsilon)\ln n$.*

7. RELATION TO PROOF COMPLEXITY

In this section we discuss our results from the propositional complexity point of view. In particular, we explain the relation between proving integrality gaps and proving lowerbounds on the rank of LS_+ proof systems. In general a *propositional proof system* is a polynomial time verifier $V(\mathcal{P}, \phi)$ that checks whether $\mathcal{P}$ is a *certificate* of the universal statement $\forall x \neg\phi(x)$, i.e., ϕ is unsatisfiable. Many (approximation) algorithms as a byproduct of their computation provide (explicitly or implicitly) a certificate that the output value lies within a certain factor to the optimum; this certificate may be considered a *propositional proof* that the given **NP**-optimization problem has no solution that achieves a certain optimization value. In the case of LS_+ cuts, the inequalities that describe the polytope $N_+^r(P)$ resulting after r rounds may be inferred from the set of initial inequalities in the Lovász-Schrijver proof system. Thus, every proof of the integrality gap for a sequence of LS_+ cuts may be considered as a lowerbound on the refutation rank in an LS_+ proof system of the tautology encoding that there exists no good solution, and vice versa. So since the propositional and computational complexity are similar for LS round lowerbounds, we have presented our results in the context of the latter in this paper. (Note that the classical propositional complexity measure would be the number of lines needed to do LS-style reasoning. However, no lowerbounds are known for this measure.)

Looking at our results then from the proof complexity angle it follows that there exist unsatisfiable random 3SAT instances for which an LS_+ proof system requires a linear number of rounds to refute, solving a problem left open in [3]. Similarly, our results for hypergraph VERTEX COVER and SET COVER show that the constraints defined by certain instances of these problems also require a linear number of rounds to refute.

The proof complexity angle can also be used to shed some intuition on the difficulties in proving integrality gaps via reductions in the LS world. Consider the standard reduction from 3SAT to VERTEX COVER where each clause is replaced by a triangle of vertices. We could now add new *auxiliary variables* for each triangle where each new variable is a function of the three variables from the triangle's corresponding clause. However, in general, when one introduces such auxiliary variables the proof complexity may change drastically. For example, weak resolution turns into the powerful Extended Frege proof system. On the other hand, in our case all auxiliary variables are locally specified so adding them should intuitively not make a big difference. Nevertheless, our arguments using protection lemmas seem to break down and a newer lowerbound idea seems necessary.

8. OPEN PROBLEMS

It seems important to extend our inapproximability results to a variety of problems. (Or to prove that actually many important optimization problems do have good slightly subexponential time approximation algorithms via the LS_+ procedure or other lift-and-project procedures.) As we noted above, reductions are problematic in this regard.

Methods based on games over expanders do not seem to help against the notoriously difficult VERTEX COVER problem: there are no expanders of degree 2. This question seems related to proving $k - \epsilon$ integrality gap for k-hypergraphs (a similar picture with these problems is observed in the PCP world). Moreover, the non-existence of appropriate expanders means we are also unable to prove gaps for MAX-2SAT.

Our result for SET COVER is interesting in a different respect: In [6] integrality gaps of $(1-\epsilon)\ln n$ are only ruled out under the assumption $\mathbf{NP} \neq \mathbf{DTIME}(n^{\log\log n})$. Since we rule out $(1-\epsilon)\ln n$ integrality gaps for $\Omega(n)$ rounds of LS_+, this strengthens the possibility that stronger PCP results are possible for this problem. In particular, it further supports the conjecture that it should be possible to rule out $(1-\epsilon)\ln n$ integrality gaps under the weaker assumption of $\mathbf{NP} \neq \mathbf{BPP}$ or even $\mathbf{NP} \neq \mathbf{P}$.

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APPENDIX

A. GRAPH THEORY LEMMAS

The following two lemmas use standard arguments from the theory of random graphs.

LEMMA A.1. *Let $\Delta(\epsilon,k,\beta) = \left(\frac{e^{\epsilon-k}}{5\beta(k-1-\epsilon)^{1+\epsilon}}\right)^{1/\epsilon}$. Then for all $\alpha, 0<\alpha<1$, and all $\epsilon>0$, there exists $\mu(\alpha)$ such that for all $\beta \geq \mu(\alpha)\alpha^{-k}$ and all δ, $0<\delta<\Delta(\epsilon,k,\beta)$, the probability that a random k-uniform hypergraph $G=(V,E)$ on n vertices with βn hyperedges (1) has no vertex cover of size smaller than $(1-\alpha)n$ and (2) H_G is a $(\delta n, k-1-\epsilon)$ expander is at least $1/2$.*

PROOF. Let $\beta = \mu(\alpha)\alpha^{-k}$ and suppose the hypergraph has βn randomly and uniformly chosen hyperedges where $\mu(\alpha)$ is chosen below. The probability that there exists a vertex cover of size $(1-\alpha)n$ equals the probability that there exists a set $S \subseteq V$, $|S| = \alpha n$, such that no edge contains only elements from S. This probability is bounded by

$$\binom{n}{\alpha n}(1-\alpha^k)^{\beta n} \leq \left(\frac{e}{\alpha}\right)^{\alpha n}(1-\alpha^k)^{\beta n} = \left(\frac{e}{\alpha}\right)^{\alpha n}\left(\frac{1}{e}\right)^{\mu(\alpha)n}.$$

Let $\mu(\alpha)>0$ be such that the above is less than $1/4$.

Now consider the bipartite graph H_G mapping E to V. Note that $|E| = \beta n$. The probability that a subset of $s=\delta n$ constraints of F does not have expansion more than $c = k-1-\epsilon$ is

$$\binom{\beta n}{s}\binom{n}{cs}\left(\frac{cs}{n}\right)^{ks} \leq \left(\frac{e\beta n}{s}\right)^{s}\left(\frac{en}{cs}\right)^{cs}\left(\frac{cs}{n}\right)^{ks} = \left[\delta^{\epsilon}\beta e^{k-\epsilon}c^{1+\epsilon}\right]^{s}.$$

Let $r = \delta^{\epsilon}\beta e^{k-\epsilon}c^{1+\epsilon}$. Then $r<1/5$ when $\delta < \left(\frac{e^{\epsilon-k}}{5\beta c^{1+\epsilon}}\right)^{1/\epsilon}$. Hence, the probability that some subset of E of size at most δn fails to have expansion greater than $k-1-\epsilon$ is bounded by

$$\sum_{s=1}^{\delta n} r^s \leq \sum_{s\geq 1} r^s = \frac{r}{1-r} < \frac{1}{4}.$$

So with probability at least $1/2$, both G has no vertex cover of size less than $(1-\alpha)n$ and H_G is a $(\delta n, k-1-\epsilon)$ expander. □

LEMMA A.2. *For any constant $\epsilon,\delta \in (0,1)$ for all n there exists an $(\epsilon-\delta)n$-regular hypergraph with n vertices and n edges that has vertex cover greater than $\log_{(1+\epsilon)} n$.*

PROOF. Let $\epsilon' = \epsilon - \delta/2$. Consider a random hypergraph G with n edges over n vertices in which every vertex belongs to an edge independently with probability ϵ'. Let $k = \log_{1+\epsilon} n$. The probability that G contains a vertex cover of size k is less than or equal

$$\binom{n}{k}\cdot\left[1-(1-\epsilon')^k\right]^m \leq n^k e^{-m\cdot(1-\epsilon')^k} = o(1).$$

Finally, with high probability every edge in G contains at least $(\epsilon'-\delta/2)n = (\epsilon-\delta)n$ elements. By removing vertices from each edge we can assume each edge contains exactly $(\epsilon-\delta)n$ elements. □

LEMMA A.3. *Let $H=(V_1,V_2,E)$ be a bipartite graph and let $S\subseteq V_1$ be such that for for all $S'\subseteq S$, $|\Gamma(S')| > k|S'|$. Assume $S=\{e_1,e_2,\ldots,e_\ell\}$. Then there exists a mapping $\eta : S \to \mathcal{P}(\Gamma(S))$ such that (1) for all $i\in[\ell]$, $|\eta(e_i)| = k+1$, and (2) for all $i\in[\ell]$, $|\eta(e_i)\setminus\bigcup_{j<i}\eta(e_j)| \geq k$.*

PROOF. By the generalization of Hall's theorem there exists a k-matching from S into $\Gamma(S)$. Fix such a k-matching ν once and for all. We construct η in the following recursive way. By assumption, $\Gamma(S)$ contains at least $\ell k+1$ elements. So by the pigeon-hole principle there exists a vertex $v\in\Gamma(S)$ which does not belong to $\bigcup_{e\in S}\nu(e)$. Consider any vertex $e\in S$ that is adjacent to v (such a point exists because $v\in\Gamma(S)$) and let $\eta(e) = \{v\}\cup\nu(e)$. Finally, denote $S' = S\setminus\{e\}$ and repeat the process recursively for S'. The vertices in S' are ordered according to the way they were ordered in S.

Clearly for all vertices e_i in S, $\eta(e_i)$ is a $k+1$ element subset of $\Gamma(S)$. To check the second required property for η note that at each step of the inductive process, no vertex of $\nu(e)$ may be joined to any of the $\eta(e')$ from earlier steps, because $\eta(e')$ consists of $\nu(e')$ and v', $v'\notin\nu(e)$. The lemma follows. □

B. LS_+ DERIVATION OF POPULAR SDP RELAXATIONS

To illustrate the power of the LS_+ procedure, we sketch how to use a few rounds of LS_+ to derive popular SDP relaxations used in famous approximation algorithms. (This was suggested by the reviewers, who pointed out that this is not very well-known.)

It will be more convenient to view LS_+ as a method for generating new inequalities. Given any relaxation

$$a_r^T x \geq b \qquad r = 1,2,\ldots,m \tag{B.1}$$

(where the trivial constraints $0 \le x_i \le 1$ are assumed to be included), one round of LS_+ produces a system of inequalities in $(n+1)^2$ variables Y_{ij} for $i,j = 0,1,\ldots,n$. As mentioned, the intended "meaning" is that $Y_{ij} = x_i x_j$ and $Y_{00} = 1, Y_{0i} = x_i = x_i x_0$, and $Y_{00} = 1$ so every quadratic expression in the x_i's can be viewed as a linear expression in the Y_{ij}'s. This is how the quadratic inequalities below should be interpreted.

$$\begin{aligned}
(1-x_i)a_r^T x &\ge (1-x_i)b \qquad && \forall i = 1,\ldots,n, \quad \forall r = 1,\ldots,m \\
x_i a_r^T x &\ge x_i b && \forall i = 1,\ldots,n, \quad \forall r = 1,\ldots,m \\
x_i x_i &= x_i x_0 && \forall i = 1,2,\ldots,n
\end{aligned}$$

(The last constraint corresponds to the fact that $x_i^2 = x_i$ for 0/1 variables.) Finally, one imposes the condition that (Y_{ij}) is positive semidefinite. Obviously, any positive combination of the above inequalities is also implied, and the derivations below will use this fact.

B.1 Deriving the GW relaxation

The Goemans-Williamson relaxation for MAX-CUT [9] involves finding unit vectors $u_1, u_2, \ldots, u_n$ so as to minimize

$$\sum_{\{i,j\}\in E} \frac{1}{4} |u_i - u_j|^2 .$$

This SDP relaxation can be derived by one round of LS_+ on the trivial linear relaxation. This relaxation has 0/1 variables x_i and d_{ij}. In the integer solution, x_i indicates which side of the cut vertex i is on, and d_{ij} is 1 iff i,j are on opposite sides of the cut.

$$\max_{\{i,j\}\in E} d_{ij} \tag{B.2}$$

$$d_{ij} \ge x_i - x_j \qquad \forall i,j = 1,2,\ldots,n \tag{B.3}$$

$$d_{ij} \le x_i + x_j \qquad \forall i,j = 1,2,\ldots,n \tag{B.4}$$

$$d_{ij} \le 2 - (x_i + x_j) \qquad \forall i,j = 1,2,\ldots,n \tag{B.5}$$

Then one round of LS_+ generates the following inequalities on d_{ij}:

$$x_i d_{ij} \ge x_i(x_i - x_j) \tag{B.6}$$

$$(1-x_i)d_{ij} \ge (1-x_i)(x_j - x_i). \tag{B.7}$$

Adding these and simplifying using the fact that $x_i^2 = x_i$ for 0/1 variables, one obtains $d_{ij} \ge (x_i - x_j)^2$. Similarly one can obtain $d_{ij} \le (x_i - x_j)^2$ whereby it follows $d_{ij} = (x_i - x_j)^2 = Y_{ii} + Y_{jj} - 2Y_{ij}$.

Now if (Y_{ij}) is any feasible solution then its Cholesky decomposition $v_0, v_1, \ldots, v_n \in \Re^{n+1}$ are vectors such that $Y_{ij} = < v_i, v_j >$. Then $d_{ij} = |v_i - v_j|^2$. Now define the set of vectors $u_1, u_2, \ldots, u_n$ as $u_i = v_0 - 2v_i$. These satisfy

$$d_{ij} = \tfrac{1}{4}|u_i - u_j|^2 \tag{B.8}$$

$$|u_i|^2 = |v_0|^2 - 4 < v_0, v_i > +4\,|v_i|^2 = 1. \tag{B.9}$$

Thus the u_i's are a feasible solution to the GW relaxation. We conclude that one round of LS_+ produces a relaxation at least as tight as the GW relaxation (and in fact one can show that the two relaxations are the same).

B.2 Deriving the ARV relaxation

Arora, Rao, and Vazirani [2] derive their $\sqrt{\log n}$-approximation for SPARSEST CUT using a similar SDP relaxation whose salient feature is the *triangle inequality*:

$$|u_i - u_j|^2 + |u_j - u_k|^2 \ge |u_i - u_k|^2 \qquad \forall i,j,k.$$

(In other words, $d_{ij} = |u_i - u_k|^2$ forms a metric space.) This relaxation minus the triangle inequality is derived similarly to the GW relaxation above (details omitted). The claim is that the triangle inequality is implied after three rounds of LS_+. As shown in [12], r rounds of LS_+ imply all inequalities on subsets of size r that are true for the integer solution. In other words, the induced solution on subsets of size r lies in the convex hull of integer solutions. Thus after three rounds the d_{ij} variables restricted to sets of size three lie in the *cut cone*. Since the cut cone is just the set of ℓ_1 (pseudo)metrics, it follows that the d_{ij} variables form a (pseudo)metric. Thus three rounds of LS_+ give a relaxation that is at least as strong as the ARV relaxation.