

Short Proofs of the Kneser-Lovász Coloring Principle¹

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Abstract

We prove that propositional translations of the Kneser-Lovász theorem have polynomial size extended Frege proofs and quasi-polynomial size Frege proofs for all fixed values of k . We present a new counting-based combinatorial proof of the Kneser-Lovász theorem that avoids the topological arguments of prior proofs for all but finitely many base cases. We introduce new “truncated Tucker lemma” principles, which are miniaturizations of the octahedral Tucker lemma. The truncated Tucker lemma implies the Kneser-Lovász theorem. We show that the $k = 1$ case of the truncated Tucker lemma has polynomial size extended Frege proofs.

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1. Introduction

This paper discusses proofs of Lovász’s theorem about the chromatic number of Kneser graphs and the proof complexity of propositional translations of the Kneser-Lovász theorem. Our main results give a new proof of the Kneser-Lovász theorem, which, for fixed parameter k , uses a simple counting argument instead of the topological arguments used in prior proofs, for all but finitely many cases. These arguments can be formalized in propositional logic to give polynomial size extended Frege proofs and quasi-polynomial size Frege proofs.

The proof complexity of Frege and extended Frege systems was first studied by Cook and Reckhow [13, 14] and Statman [29]. Frege systems (denoted \mathcal{F}) are sound and complete proof systems for propositional logic with a finite set of schemes for axioms and inference rules. The typical example is a “textbook style” propositional proof system using modus ponens as its only rule of inference. In fact, all Frege systems are equivalent to this system [14]. Extended Frege systems (denoted $e\mathcal{F}$) are Frege systems augmented with the extension rule, which allows variables to abbreviate complex formulas. The reader unfamiliar with Frege systems can consult the surveys [5, 10, 11, 14, 22, 28] for more information.

The *size* of a Frege or extended Frege proof is the number of symbols in the proof. A proof system \mathcal{P}_1 *simulates* a proof system \mathcal{P}_2 if and only if there is a polynomial $p(n)$ such that, for any propositional formula φ , if φ has a \mathcal{P}_2 -proof of size n , then φ has a \mathcal{P}_1 -proof of size $\leq p(n)$. Also, \mathcal{P}_1 *quasi-polynomially simulates* \mathcal{P}_2 if and only if there is a $k > 0$ such that, if φ has a \mathcal{P}_2 -proof of size n then φ has a \mathcal{P}_1 -proof of size $2^{(\log n)^k}$. It is trivial that extended Frege systems simulate Frege systems.

It is generally conjectured that the extension rule can provide substantial shortening of proof length, and therefore that Frege systems do not (quasi-polynomially) simulate extended Frege systems. The intuition is that Frege proofs are able to reason using Boolean formulas; whereas extended Frege proofs can reason using Boolean circuits. (See [20] for a formalization of this intuition.) Boolean formulas are conjectured to require exponential size to simulate Boolean circuits. There is no known direct connection to proof complexity, but it is generally conjectured by analogy that there is an exponential separation between the sizes of Frege proofs and extended Frege proofs, and thus that Frege systems do not (quasi-polynomially) simulate extended Frege systems.

Bonet, Buss, and Pitassi [5] systematically looked for combinatorial tautologies that could be candidates for exponentially separating proof sizes for Frege and extended Frege systems. Surprisingly, they found only a small number. The first candidates were based on linear algebra, including the Oddtown theorem, the Graham–Pollack theorem, the Fisher Inequality, the Ray-Chaudhuri–Wilson theorem, and the $AB = I \Rightarrow BA = I$ tautology (the last was suggested by S. Cook). The remaining candidate was Frankl’s theorem on the trace of

sets. All of these principles were shown to have polynomial size extended Frege proofs, but it was open whether they had polynomial size Frege proofs.

Hrubeš and Tzameret [18] recently showed that the five tautologies based on linear algebra have quasi-polynomial size Frege proofs by showing that there are quasi-polynomial size definitions of determinants whose properties can be established by quasi-polynomial Frege proofs (as was conjectured by [5]). Subsequently, Aisenberg, Bonet, and Buss [1] showed that Frankl’s theorem also has quasi-polynomial size Frege proofs. With these results, none of the principles considered by Bonet-Buss-Pitassi provide an exponential separation of Frege and extended Frege systems.

An earlier combinatorial candidate was the pigeonhole principle, introduced by Cook and Reckhow [14]. They showed this has polynomial size extended Frege proofs. Buss [8] later showed this also has polynomial size Frege proofs. Buss’s proof was based on “counting”, and showed that Frege proofs can use polynomial size formulas (based on carry-save addition) to define sizes of sets, and can reason about sizes effectively. Carry-save addition also allows Frege systems to reason about integer multiplication and about adding vectors of integers. The ability of Frege proofs to “count” and to reason about sizes of sets will be important for our Frege proofs of the Kneser-Lovász theorem. The counting proofs were quite different than Cook and Reckhow’s inductive proofs of the pigeonhole principle, so these were sometimes taken as evidence that Frege systems do not (quasi-polynomially) simulate Frege proofs. However, [6] recently showed that Cook and Reckhow’s inductive proofs can be reformulated as quasi-polynomial size Frege proofs.

Another class of candidates is based on consistency statements. We write $\text{Con}_{\mathcal{P}}(n)$ for the propositional statement expressing the condition that the proof system \mathcal{P} does not have a proof of $p \wedge \neg p$ of size $\leq n$. For “natural” systems \mathcal{P} (including Frege and extended Frege systems), the formula $\text{Con}_{\mathcal{P}}(n)$ has size polynomially bounded by n (e.g., [12, 9]). Propositional consistency statements have been studied for first-order systems by Pudlák [26, 27] and Friedman [unpublished]. Pudlák showed that axiomatizable theories of arithmetic have polynomial size (first-order) proofs of their partial consistency statements; Pudlák and Friedman independently proved polynomial lower bounds as well. Cook [12] showed that an extended Frege system has polynomial size proofs of its own partial consistency statements $\text{Con}_{e\mathcal{F}}(n)$. Buss [9] proved similarly that a Frege system has polynomial size proofs of its partial consistency statements $\text{Con}_{\mathcal{F}}(n)$.

It also follows from [9] that Frege systems (quasi-)polynomially simulate extended Frege systems iff there are (quasi-)polynomial size Frege proofs of $\text{Con}_{e\mathcal{F}}(n)$. In addition, $\text{Con}_{e\mathcal{F}}(n)$ is a “logical” principle not really a “combinatorial” principle.⁶ For these reasons, partial consistency statements such as $\text{Con}_{e\mathcal{F}}(n)$ do not serve as the kinds of candidates for separating Frege and extended Frege system that we are seeking.

Other candidates for exponentially separating Frege and extended Frege sys-

⁶However, see Avigad [3] for a combinatorial version of $\text{Con}_{e\mathcal{F}}(n)$.

tems arose from the work of Kołodziejczyk, Nguyen, and Thapen [21] in the setting of bounded arithmetic [7]. These include various forms of the local improvement principles LI, LI_{\log} and LLI. The results of [21] showed that the LI principle is many-one complete for the NP search problems of V_2^1 ; it follows that LI is equivalent to partial consistency statements for extended Frege systems. Beckmann and Buss [4] subsequently proved that LI_{\log} is provably equivalent (in S_2^1) to LI and that the linear local improvement principle LLI is provable in U_2^1 . The LLI principle thus has quasi-polynomial size Frege proofs. Combining the results of [4, 21] shows that LI_{\log} and LLI are many-one complete for the NP search problems of V_2^1 and U_2^1 , respectively, and thus equivalent to partial consistency statements for extended Frege and Frege systems, respectively.

Thus, apart from partial consistency statement, none of the above principles serve as combinatorial candidates for showing that Frege systems do not quasi-polynomially simulate extended Frege systems.

A new candidate based on the Kneser-Lovász theorem was recently proposed by Istrate and Crăciun [19]. As defined below, the Kneser-Lovász theorem gives a lower bound on the chromatic of the (n, k) -Kneser graphs. Istrate and Crăciun showed that the $k = 3$ case of these tautologies have polynomial size extended Frege proofs, but left open whether they have (quasi-)polynomial size Frege proofs. However, the main results of the present paper show that, for any fixed $k \geq 1$, the Kneser-Lovász tautologies have quasi-polynomial size Frege proofs. Thus these also do not give an exponential separation of Frege from extended Frege systems.

With these last results, we have few remaining combinatorial candidates for showing Frege systems do not quasi-polynomially simulate extended Frege systems. One remaining candidate is tautologies based on the Rectangular Local Improvement principles, RLI_k , of Beckmann-Buss [4] for fixed $k \geq 2$. The only other combinatorial candidate we know of is introduced in Section 6 below. This is the $k = 1$ case of the “truncated Tucker lemma”. Theorem 26 shows it has polynomial size extended Frege proofs; however, we have been unable to show that it has quasi-polynomial size Frege proofs.

The outline of the paper is as follows. First, in Section 2 we define the (n, k) -Kneser graphs and state Lovász’s theorem about their chromatic numbers. Theorems 4 and 5 state our main results about Frege and extended Frege proofs of that theorem. Section 3 gives an informal (“mathematical”) proof of the Kneser-Lovász theorem using a new proof method based on a simple counting argument. Prior proofs used, at least implicitly, a topological fixed-point lemma. The most combinatorial proof is by Matoušek [24] and is inspired by the octahedral Tucker lemma; see also Ziegler [30]. Our new proofs mostly avoid topological arguments and use a counting argument instead. The counting arguments are used to prove the existence of “star-shaped” color classes. These counting arguments can be formalized with Frege proofs. For the Kneser-Lovász theorem, the counting arguments reduce the general case to “small” instances of size $n \leq 2k^4$. For fixed k , there are only finitely many small instances, and they can be verified by exhaustive enumeration. As we shall see, this leads to polyno-

mial size extended Frege proofs, and quasi-polynomial size Frege proofs for the Kneser-Lovász principles. Sections 3.1 and 3.2 give two “mathematical” versions of the counting proofs, which will be formalized as extended Frege proofs and Frege proofs (respectively). Section 3.3 is a short diversion and considers whether there are colorings of the Kneser graphs with many non-star-shaped color classes.

Section 4 discusses some of the details of formalizing the arguments in Section 3 in the Frege and extended Frege systems, establishing our two main theorems. We focus on expressing the concepts described in Section 3 in propositional logic, and we only sketch some of the details of how Frege systems can prove properties of these concepts.

The proofs of the Kneser-Lovász theorem in Sections 3 and 4 reduce the general case of the Kneser-Lovász theorem to finitely many base cases, which are then handled by exhaustive enumeration. It would be interesting to give a uniform proof that does not need to handle the base cases in this way. Motivated by this, Section 5 defines new “truncated” forms of the Tucker lemma. These truncated Tucker lemmas can be expressed as families of polynomial size propositional tautologies. The octahedral Tucker lemma, on the other hand, can only be expressed by exponential size formulas. Matoušek showed that the Kneser-Lovász theorem follows from the Tucker lemma. We refine this by showing that the Tucker lemma implies the two truncated Tucker lemmas, the two versions of the truncated Tucker lemma are equivalent, and that the truncated Tucker lemmas imply the Kneser-Lovász theorem. Since the truncated Tucker lemmas can be expressed as polynomial size tautologies, it is natural to ask about their proof complexity in (extended) Frege systems. Section 6 proves that the $k = 1$ cases of the truncated Tucker lemmas have polynomial size extended Frege proofs. It is open whether these have (quasi-)polynomial size Frege proofs. Thus, this is a candidate for separating the Frege and extended Frege systems. Likewise, it is open whether the truncated Tucker lemmas for $k > 1$ have subexponential size extended Frege proofs. It is tempting to try to modify the combinatorial proof of the Tucker lemma by Freund and Todd [17] (see also Matoušek [24]), but we have been unable to express this argument with polynomial size extended Frege proofs. Freund and Todd’s argument uses a version of the parity principle PPA [25]; indeed, Papadimitriou [25] notes that the arguments of Freund [15, 16] show that the Tucker lemma can be proved using a directed parity principle PPAD. The difficulty with translating these arguments to extended Frege proofs is that they apply the parity principle on exponentially large graphs.

2. The Kneser-Lovász Principle and Statement of the Main Theorems

The (n, k) -Kneser graph is defined to be the undirected graph whose vertices are the k -subsets of $\{1, \dots, n\}$; there is an edge between two vertices iff those vertices have empty intersection. The Kneser-Lovász theorem states that Kneser graphs have a large chromatic number:

Theorem 1 (Lovász [23]). *Let $n \geq 2k > 1$. The (n, k) -Kneser graph has no coloring with $n - 2k + 1$ colors.*

It is well-known that the (n, k) -Kneser graph has a coloring with $n - 2k + 2$ colors (see Section 3.3), so the bound $n - 2k + 1$ is optimal. For $k = 1$, the Kneser-Lovász theorem is just the pigeonhole principle.

Istrate and Crăciun [19] noted that, for fixed values of k , the propositional translations of the Kneser-Lovász theorem have polynomial size in n . They presented proofs that can be formalized by polynomial size Frege proofs for $k = 2$, and by polynomial size extended Frege proofs for $k = 3$. This left open the possibility that the $k = 3$ case could exponentially separate the Frege and extended Frege systems. It was also left open whether the $k > 3$ case of the Kneser-Lovász theorem gave tautologies that require exponential size extended Frege proofs. As discussed above, the present paper refutes these possibilities. Theorems 4 and 5 summarize these results.

Let $[n]$ be the set $\{1, \dots, n\}$; members of $[n]$ are called *nodes*. We identify $\binom{n}{k}$ with the set of k -subsets of $[n]$, the *vertices* of the (n, k) -Kneser graph.

Definition 2. An m -coloring of the (n, k) -Kneser graph is a map c from $\binom{n}{k}$ to $[m]$, such that for $S, T \in \binom{n}{k}$, if $S \cap T = \emptyset$, then $c(S) \neq c(T)$. If $\ell \in [m]$, then the *color class* P_ℓ is the set of vertices assigned the color ℓ by c .

The formulas Kneser_k^n are the natural propositional translations of the statement that there is no $(n - 2k + 1)$ -coloring of the (n, k) -Kneser graph:

Definition 3. Let $n \geq 2k > 1$, and $m = n - 2k + 1$. For $S \in \binom{n}{k}$ and $i \in [m]$, the propositional variable $p_{S,i}$ has the intended meaning that vertex S of the Kneser graph is assigned the color i . The formula Kneser_k^n is

$$\bigwedge_{S \in \binom{n}{k}} \bigvee_{i \in [m]} p_{S,i} \rightarrow \bigvee_{\substack{S, T \in \binom{n}{k} \\ S \cap T = \emptyset}} \bigvee_{i \in [m]} (p_{S,i} \wedge p_{T,i}).$$

Theorem 4. *For fixed parameter $k \geq 1$, the propositional translations Kneser_k^n of the Kneser-Lovász theorem have polynomial size extended Frege proofs.*

Theorem 5. *For fixed parameter $k \geq 1$, the propositional translations Kneser_k^n of the Kneser-Lovász theorem have quasi-polynomial size Frege proofs.*

When both k and n are allowed to vary, it is open whether the Kneser_k^n tautologies have quasi-polynomial size (extended) Frege proofs, or equivalently, have proofs with size quasi-polynomially bounded in terms of n^k .

3. Mathematical Arguments

Section 3.1 gives the new proof of the Kneser-Lovász theorem; this is later shown to be formalizable with polynomial size extended Frege proofs. Section 3.2 gives a slightly more complicated but more efficient proof, later shown

to be formalizable with quasi-polynomial size Frege proofs. The next definition and lemma are crucial for Sections 3.1 and 3.2.

Any two vertices in a color class P_ℓ have nonempty intersection. One way this can happen is for the color class to be “star-shaped”:

Definition 6. A color class P_ℓ is *star-shaped* if $\bigcap P_\ell$ is nonempty. If P_ℓ is star-shaped, then any $i \in \bigcap P_\ell$ is called a *central node* of P_ℓ .

The next lemma bounds the size of color classes that are not star-shaped. It will be used in our proof of the Kneser-Lovász theorem to establish the existence of star-shaped color classes. The idea is that non-star-shaped color classes are too small to cover all $\binom{n}{k}$ vertices.

Lemma 7. *Let c be a coloring of $\binom{n}{k}$. If P_ℓ is not star-shaped, then*

$$|P_\ell| \leq k^2 \binom{n-2}{k-2}.$$

Proof. Suppose P_ℓ is not star-shaped. If P_ℓ is empty, the claim is trivial. So suppose $P_\ell \neq \emptyset$, and let $S_0 = \{a_1, \dots, a_k\}$ be some element of P_ℓ . Since P_ℓ is not star-shaped, there must be sets $S_1, \dots, S_k \in P_\ell$ with $a_i \notin S_i$ for $i = 1, \dots, k$.

To specify an arbitrary element S of P_ℓ , we do the following. Since S and S_0 have the same color, $S \cap S_0$ is nonempty. We first specify some $a_i \in S \cap S_0$. Likewise, $S \cap S_i$ is nonempty; we second specify some $b \in S \cap S_i$. By construction, $a_i \neq b$, so S is fully specified by the k possible values for a_i , the k possible values for b , and the $\binom{n-2}{k-2}$ possible values for the remaining members of S . Therefore, $|P_\ell| \leq k^2 \binom{n-2}{k-2}$. \square

3.1. Argument for Extended Frege Proofs

Let $k > 1$ be fixed. We prove the Kneser-Lovász theorem by induction on n . The base cases for the induction are $n = 2k, \dots, N(k)$ where $N(k)$ is the constant depending on k specified in Lemma 8. We shall show that $N(k)$ is no greater than k^4 . Since k is fixed, there are only finitely many base cases. Since the Kneser-Lovász theorem is true, these base cases can all be proved by a fixed Frege proof of finite size (depending on k). Therefore, in our proof below, we only show the induction step.

Lemma 8. *Fix $k > 1$. There is an $N(k)$ so that, for $n > N(k)$, any $(n-2k+1)$ -coloring of $\binom{n}{k}$ has at least one star-shaped color class.*

Proof. Suppose that a coloring c has no star-shaped color class. Since there are $n - 2k + 1$ many color classes, Lemma 7 implies that

$$(n - 2k + 1) \cdot k^2 \binom{n-2}{k-2} \geq \binom{n}{k}. \quad (1)$$

For fixed k , the left-hand side of (1) is $\Theta(n^{k-1})$ and the right-hand side is $\Theta(n^k)$. Thus, there exists an $N(k)$ such that (1) fails for all $n > N(k)$. Hence for $n > N(k)$, there must be at least one star-shaped color class. \square

To obtain an upper bound on the value of $N(k)$, note that (1) is equivalent to

$$(n - 2k + 1)k^3(k - 1) \geq n(n - 1). \quad (2)$$

Since $2k - 1 \geq 1$, (2) implies that $(n - 1)k^4 > n(n - 1)$ and thus that $n < k^4$. Thus, (1) will be false if $n \geq k^4$; so $N(k) < k^4$.

We are now ready to give our first proof of the Kneser-Lovász theorem.

Proof of Theorem 1, except for base cases. Fix $k > 1$. By Lemma 8, there is some $N(k)$ such that for $n > N(k)$, any $(n - 2k + 1)$ -coloring c of $\binom{n}{k}$ has a star-shaped color class. As discussed above, the cases where $n \leq N(k)$ are handled by exhaustive search and the truth of the Kneser-Lovász theorem. For $n > N(k)$, we prove Theorem 1 by infinite descent. In other words, we show that if c is an $(n - 2k + 1)$ -coloring of $\binom{n}{k}$, then there is some c' that is an $((n - 1) - 2k + 1)$ -coloring of $\binom{n-1}{k}$.

By Lemma 8, the coloring c has some star-shaped color class P_ℓ with central node i . Without loss of generality, $i = n$ and $\ell = n - 2k + 1$. Let

$$c' = c \upharpoonright \binom{n-1}{k}$$

be the restriction of c to the domain $\binom{n-1}{k}$. This discards the central node n of P_ℓ , and thus all vertices with color ℓ . Therefore, c' is an $((n - 1) - 2k + 1)$ -coloring of $\binom{n-1}{k}$. This completes the proof. \square

3.2. Argument for Frege Proofs

We now give a second proof of the Kneser-Lovász theorem. The proof above required $n - N(k)$ rounds of infinite descent to transform a Kneser graph on n nodes to one on $N(k)$ nodes. Our second proof replaces this with only $O(\log n)$ many rounds, and this efficiency will be key for formalizing this proof with quasi-polynomial size Frege proofs in Section 4.2.

We refine Lemma 8 to show that for n sufficiently large, there are many (i.e., a constant fraction) star-shaped color classes. The idea is to combine the upper bound of Lemma 7 on the size of non-star-shaped color classes with the trivial upper bound of $\binom{n-1}{k-1}$ on the size of star-shaped color classes.

Lemma 9. *Fix $k > 1$ and $0 < \beta < 1$. Then there exists an $N(k, \beta)$ such that for $n > N(k, \beta)$, if c is an $(n - 2k + 1)$ -coloring of $\binom{n}{k}$, then c has at least $\frac{n}{k}\beta$ many star-shaped color classes.*

Proof. The value of $N(k, \beta)$ can be set equal to $\frac{k^3(k-\beta)}{1-\beta}$. Let $n > \frac{k^3(k-\beta)}{1-\beta}$, and suppose c is an $(n - 2k + 1)$ -coloring of $\binom{n}{k}$. Let α be the number of star-shaped color classes of c . It is clear that an upper bound on the size of each star-shaped color class is $\binom{n-1}{k-1}$. There are $n - \alpha - 2k + 1$ many non-star-shaped classes, and Lemma 7 bounds their size by $k^2 \binom{n-2}{k-2}$. This implies that

$$\binom{n-1}{k-1}\alpha + k^2 \binom{n-2}{k-2}(n - \alpha - 2k + 1) \geq \binom{n}{k}. \quad (3)$$

Assume for a contradiction that $\alpha < \frac{n}{k}\beta$. Since $n > \frac{k^3(k-\beta)}{1-\beta}$, $0 < \beta < 1$, and $k \geq 2$, we have $n-1 > k^3(k-1) > k^2(k-1)$. Therefore, $\binom{n-1}{k-1} > k^2\binom{n-2}{k-2}$, and if α is replaced by the larger value $\frac{n}{k}\beta$, the left hand side of (3) increases. Thus,

$$\binom{n-1}{k-1} \frac{n}{k}\beta + k^2 \binom{n-2}{k-2} \left(n - \frac{n}{k}\beta - 2k + 1\right) > \binom{n}{k}.$$

Since $\binom{n-1}{k-1} \frac{n}{k} = \binom{n}{k}$ and $n - \frac{n}{k}\beta - 2k + 1 = \frac{k-\beta}{k}n - 2k + 1$,

$$k^2 \binom{n-2}{k-2} \left(\frac{k-\beta}{k}n - 2k + 1\right) > (1-\beta) \binom{n}{k}.$$

Expanding the binomial coefficients yields

$$k^3(k-1) \left(\frac{k-\beta}{k}n - 2k + 1\right) > (1-\beta)n(n-1).$$

We have $\frac{k-\beta}{k}(n-1) > \frac{k-\beta}{k}n - 2k + 1$. Therefore,

$$k^3(k-1) \frac{k-\beta}{k}(n-1) > (1-\beta)n(n-1).$$

Dividing by $n-1$ gives $k^3(k-\beta) > (1-\beta)n$, contradicting $n > \frac{k^3(k-\beta)}{1-\beta}$. \square

We now give our second proof of the Kneser-Lovász theorem.

Proof of Theorem 1, except for base cases. Fix $k > 1$. By Lemma 9 with $\beta = 1/2$, if $n > N(k, 1/2)$ and c is an $(n-2k+1)$ -coloring of $\binom{n}{k}$, then c has at least $n/2k$ many star-shaped color classes. We prove the Kneser-Lovász theorem by induction on n . The base cases are where $2k \leq n \leq N(k, 1/2)$, and there are only finitely of these, so they can be exhaustively proven. For $n > N(k, 1/2)$, we structure the induction proof as an infinite descent. In other words, we show that if c is an $(n-2k+1)$ -coloring of $\binom{n}{k}$, then there is some c' that is an $((n - \frac{n}{2k}) - 2k + 1)$ -coloring of $\binom{n - \frac{n}{2k}}{k}$. For simplicity of notation, we assume $\frac{n}{2k}$ is an integer. If this is not the case, we really mean to round up to the nearest integer $\lceil \frac{n}{2k} \rceil$.

By permuting the color classes and the nodes, we can assume w.l.o.g. that the $\frac{n}{2k}$ color classes P_ℓ for $\ell = n - \frac{n}{2k} - 2k + 2, \dots, n - 2k + 1$ are star-shaped, and each such P_ℓ has a central node in $\{n - (n/2k) + 1, \dots, n\}$. That is, the last $\frac{n}{2k}$ many color classes are star-shaped, and they all have a central node among the last $\frac{n}{2k}$ nodes in $[n]$. We shall discard these $n/2k$ many star-shaped color classes, and the topmost $n/2k$ many nodes. This discards the central nodes of the discarded color classes, thereby removing all the vertices of the Kneser graph which are assigned discarded color classes. (It is possible that some star-shaped color classes share central nodes. We only need to be sure to discard at least one central node for each color classes, and thus, in this case, additional nodes can be discarded so that $n/2k$ are discarded in all.)

More formally, define c' to be the coloring of $\binom{n-n/2k}{k}$ which assigns the same colors as c . The map c' is a $(\frac{2k-1}{2k}n - 2k + 1)$ -coloring of $\binom{\frac{2k-1}{2k}n}{k}$, since $n - \frac{n}{2k} = \frac{2k-1}{2k}n$. This completes the proof of the induction step. \square

When formalizing the above argument with quasi-polynomial size Frege proofs, it will be important to know how many iterations of the procedure are required to reach the base cases, so let us calculate this.

After s iterations of this procedure, we have a $(\frac{2k-1}{2k})^s n - 2k + 1$ -coloring of $\binom{(\frac{2k-1}{2k})^s n}{k}$. We pick s large enough so that $(\frac{2k-1}{2k})^s n$ is less than $N(k, 1/2)$. In other words, since k is constant,

$$s = \log_{\frac{2k-1}{2k}} \left(\frac{n}{k^3(2k-1)} \right) = O(\log n)$$

will suffice, and only $O(\log n)$ many rounds of the procedure are required.

3.3. Optimal Colorings of Kneser Graphs

This section is a brief diversion motivated by the question of whether Lemma 9 about the number of non-star-shaped colors is optimal.

It is well-known that $\binom{n}{k}$ has an $(n - 2k + 2)$ -coloring [23]. A simple construction of such a coloring, which we call c_1 , is given here for completeness as follows. For $S \in \binom{n}{k}$, define $c_1(S)$ by:

- (1) If $S \not\subseteq [2k - 1]$, let $c_1(S) = \max(S) - (2k - 2)$. Clearly $1 < c_1(S) \leq n - 2k + 2$.
- (2) If $S \subseteq [2k - 1]$, let $c_1(S) = 1$.

We claim that c_1 defines a proper coloring. By construction, if $c_1(S) > 1$, then $c_1(S) + (2k - 2) \in S$. Thus, if $c_1(S) = c_1(S') > 1$, then $S \cap S' \neq \emptyset$ and S and S' are not joined by an edge in the Kneser graph. On the other hand, if $c_1(S) = 1$, then S contains k elements from the set $[2k - 1]$. Any two such subsets have nonempty intersection, and therefore if $c_1(S) = c_1(S') = 1$, then again $S \cap S' \neq \emptyset$. Note that c_1 contains $n - 2k + 1$ many star-shaped color classes, and only one non-star-shaped color class.

In view of Lemma 9, it is interesting to ask whether it is possible to give $(n - 2k + 2)$ -colorings with fewer star-shaped color classes and more non-star-shaped color classes. The next theorem gives the best construction we know.

Theorem 10. *Let $k \geq 1$ and $n \geq 3k + 3$. There is an $(n - 2k + 2)$ coloring c_{k-1} of $\binom{n}{k}$ which has $k - 1$ many non-star-shaped color classes and only $n - 3k + 3$ many star-shaped color classes.*

Proof. To construct c_{k-1} , partition the set $[n]$ into $n - 2k + 2$ many subsets T_1, \dots, T_{n-2k+2} as follows. For $i \leq n - 3k + 3$, T_i is chosen to be a singleton set, say $T_i = \{n - i + 1\}$. The remaining $k - 1$ many T_i 's are subsets of size 3, say

$T_i = \{j-2, j-1, j\}$ where $j = 3(i - (n - 3k + 3))$. Since $n = (n - 3k + 3) + 3(k - 1)$, the sets T_i partition $[n]$, and each T_i has cardinality either 1 or 3. For S a subset of n of cardinality k , define the color $c_{k-1}(S)$ to equal the least i such that

$$|S \cap T_i| > \frac{1}{2}|T_i|.$$

We claim there must exist such an i . If not, then S contains no members of the singleton subsets T_i and at most one member of each of the subsets T_i of size three. But there are only $k - 1$ many subsets of size three, contradicting $|S| = k$.

It is easy to check that if $c_{k-1}(S) = c_{k-1}(S')$ then $S \cap S' \neq \emptyset$. Thus c_{k-1} is a coloring. Furthermore, c_{k-1} has $k - 1$ many non-star-shaped color classes and $n - 3k + 3$ many star-shaped color classes. \square

Theorem 10 can be extended to show that when $n < 3k + 3$, there is a $n - 2k + 2$ coloring with no star-shaped color class. The proof construction uses a similar idea, based on the fact that $[n]$ can be partitioned into $n - 2k + 2$ many subsets, each of odd cardinality ≥ 3 . We leave the details to the reader.

Question 11. *Do there exist $(n - 2k + 2)$ -colorings of the (n, k) -Kneser graphs with more than $k - 1$ many non-star-shaped color classes?*

4. Formalization in Propositional Logic

4.1. Polynomial Size Extended Frege Proofs

We sketch the formalization of the argument in Section 3.1 as a polynomial size extended Frege proof, establishing Theorem 4. We concentrate on showing how to express concepts such as “star-shaped color class” with polynomial size propositional formulas. For expository reasons, we omit the straightforward details of how (extended) Frege proofs can prove properties of these concepts.

Fix values for k and n with $n > N(k)$. We describe an extended Frege proof of Kneser_k^n . We have variables $p_{S,j}$ (recall Definition 3), collectively denoted \vec{p} . The proof assumes $\text{Kneser}_k^n(\vec{p})$ is false, and proceeds by contradiction. The main step is to define new variables \vec{p}' with the extension rule and prove that $\text{Kneser}_k^{n-1}(\vec{p}')$ fails. This will be repeated until reaching a Kneser graph over only $N(k)$ nodes.

For this, let $\text{Star}(i, \ell)$ be a formula that is true when $i \in [n]$ is a central node of the color class P_ℓ ; namely,

$$\text{Star}(i, \ell) := \bigwedge_{S \in \binom{[n]}{k}, i \notin S} \neg p_{S, \ell}.$$

Note that P_ℓ may have more than one central node. Conversely, a node i may be a central node for more than one color class.

We use $\text{Star}(\ell) := \bigvee_i \text{Star}(i, \ell)$ to express that P_ℓ is star-shaped.

The extended Frege proof defines an instance of the Kneser-Lovász principle Kneser_k^{n-1} by discarding one node and one color. The first star-shaped color class P_ℓ is discarded; accordingly, we let

$$\text{DiscardColor}(\ell) := \text{Star}(\ell) \wedge \bigwedge_{\ell' < \ell} \neg \text{Star}(\ell').$$

The node to be discarded is the least central node of the discarded P_ℓ :

$$\text{DiscardNode}(i) := \bigvee_{\ell} \left[\text{DiscardColor}(\ell) \wedge \text{Star}(i, \ell) \wedge \bigwedge_{i' < i} \neg \text{Star}(i', \ell) \right].$$

After discarding the node i and the color ℓ , the remaining nodes and colors are renumbered to the ranges $[n-1]$ and $[n-2k]$, respectively. In particular, the “new” color j (in the instance of Kneser_k^{n-1}) corresponds to the “old” color $j^{-\ell}$ (in the instance of Kneser_k^n) where

$$j^{-\ell} = \begin{cases} j & \text{if } j < \ell \\ j + 1 & \text{if } j \geq \ell. \end{cases}$$

And, if $S = \{i_1, \dots, i_k\} \in \binom{[n-1]}{k}$ is a “new” vertex (for the Kneser_k^{n-1} instance), then it corresponds to the “old” vertex $S^{-i} \in \binom{[n]}{k}$ (for the instance of Kneser_k^n), where $S^{-i} = \{i'_1, i'_2, \dots, i'_k\}$ with

$$i'_t = \begin{cases} i_t & \text{if } i_t < i \\ i_t + 1 & \text{if } i_t \geq i. \end{cases}$$

For each $S \in \binom{[n-1]}{k}$ and $j \in [n-2k]$, the extended Frege proof uses the extension rule to introduce a new variable $p'_{S,j}$ defined as follows

$$p'_{S,j} \equiv \bigvee_{i, \ell} (\text{DiscardNode}(i) \wedge \text{DiscardColor}(\ell) \wedge p_{S^{-i}, j^{-\ell}}).$$

As seen in the definition by extension, $p'_{S,j}$ is defined by cases, one for each possible pair i, ℓ of nodes and colors such that the node i is the least central node of the P_ℓ color class, where P_ℓ is the first star-shaped color class. The extended Frege proof then shows that $\neg \text{Kneser}_k^n(\vec{p})$ implies $\neg \text{Kneser}_k^{n-1}(\vec{p}')$, i.e., that if the variables $p_{S,j}$ define a coloring, then the variables $p'_{S,j}$ also define a coloring. The first step for the extended Frege proof is to show that there is at least one star-shaped color class, and then there is a unique ℓ such that $\text{DiscardColor}(\ell)$ holds. In fact, we claim there are polynomial size Frege proofs of

$$\bigvee_{\ell} \text{DiscardColor}(\ell)$$

and

$$\bigwedge_{\ell_1 < \ell_2} (\neg \text{DiscardColor}(\ell_1) \vee \neg \text{DiscardColor}(\ell_2)).$$

These assertions are proved using the proof of Lemma 8, and the counting techniques which can be formalized in Frege proofs. Note that we only need to count numbers of vertices in $\binom{n}{k}$; hence, for fixed k , we are only counting sets of polynomial size. Therefore, polynomial size Frege proofs can carry out the proof of Lemma 8. For similar reasons, there are polynomial size Frege proofs that there is a unique value $i \in [n-2k+1]$ which satisfies $\text{DiscardNode}(i)$.

For fixed values of ℓ and i , a polynomial size Frege proof now establishes

$$\text{DiscardColor}(\ell) \wedge \text{DiscardNode}(i) \wedge \text{Kneser}_k^{n-1}(\vec{p}') \rightarrow \text{Kneser}_k^n(\vec{p}).$$

This Frege proof argues as follows, assuming $\text{DiscardColor}(\ell)$ and $\text{DiscardNode}(i)$ and $\text{Kneser}_k^{n-1}(\vec{p}')$. Since $\text{Kneser}_k^{n-1}(\vec{p}')$ is true, either (a) its hypothesis is false and we have $\bigwedge_{j=1}^{n-2k} \neg p'_{S,j}$ for some $S \in \binom{n}{k}$ or (b) its conclusion is true and there are $S, T \in \binom{n}{k}$ and j such that $S \cap T = \emptyset$ and $p'_{S,j}$ and $p'_{T,j}$. If (a) holds then $\neg p_{S^{-i}, j^{-\ell}}$ for all $j \in [n-2k]$ and this together with the fact that $i \notin S^{-i}$ and i and ℓ were discarded further implies that the hypothesis of $\text{Kneser}_k^n(\vec{p})$ is false so $\text{Kneser}_k^n(\vec{p})$ is true. Likewise, if (b) holds, then using S^{-i} and T^{-i} and $j^{-\ell}$ shows that that the conclusion of Kneser_k^n is true.

Putting all these arguments together gives the desired Frege proof of

$$\neg \text{Kneser}_k^n(\vec{p}) \rightarrow \neg \text{Kneser}_k^{n-1}(\vec{p}').$$

The extended Frege proof iterates this process of removing one node and one color until it is shown that there is a coloring of $\binom{N(k)}{k}$. This is then refuted by exhaustively considering all graphs with $\leq N(k)$ nodes. \square

4.2. Quasi-polynomial Size Frege Proofs

This section discusses some of the details of the formalization of the argument in Section 3.2 as quasi-polynomial size Frege proofs, establishing Theorem 5. First we will form an extended Frege proof, then modify it to become a Frege proof. As before, the proof starts with the assumption that $\text{Kneser}_k^n(\vec{p})$ is false. As we describe next, the extended Frege proof then introduces variables \vec{p}' by extension so that $\text{Kneser}_k^{n-n/2k}(\vec{p}')$ is false. This process will be repeated $O(\log n)$ times. The final Frege proof is obtained by unwinding the definitions by extension.

For a set X of formulas and $t > 0$, we now use the notation “ $|X| \leq t$ ” to denote a formula that is true when the number of true formulas in X is less than or equal to t . As already discussed, “ $|X| \leq t$ ” can be expressed by a formula of size polynomially bounded by the total size of the formulas in X , using the construction in [8]. “ $|X| = t$ ” is defined similarly.

The formulas $\text{Star}(i, \ell)$ and $\text{Star}(\ell)$ are the same as in Section 4.1. A color ℓ is now discarded if it is among the least $n/2k$ star-shaped color classes.

$$\text{DiscardColor}(\ell) := \text{Star}(\ell) \wedge (|\{\text{Star}(\ell') : \ell' \leq \ell\}| \leq n/2k)$$

The discarded nodes are the least central nodes of the discarded color classes.

$$\text{DiscardNode}(i) := \bigvee_{\ell} \left[\text{DiscardColor}(\ell) \wedge \text{Star}(i, \ell) \wedge \bigwedge_{i' < i} \neg \text{Star}(i', \ell) \right].$$

$\text{DiscardNode}(i)$ will hold for at most $n/2k$ many nodes i , since there are only $n/2k$ many discarded colors. We could modify the definition of DiscardNode to discard exactly $n/2k$ many nodes; however, this is not strictly necessary, as the only use of DiscardNode is to define the predicate $\text{RenumNode}(i', i)$ below, and that definition effectively discards exactly $n/2k$ many nodes even if $\text{DiscardNode}(i)$ picks out fewer than $n/2k$ many nodes to be discarded.

The remaining, non-discarded colors and nodes are renumbered to form an instance of $\text{Kneser}_k^{n-n/2k}$. For this, the formula $\text{RenumNode}(i', i)$ is true when the node i' is the i th node that is not discarded; similarly $\text{RenumColor}(j', j)$ is true when the color j' is the j th color that is not discarded.

$$\begin{aligned} \text{RenumNode}(i', i) &:= (|\{\neg\text{DiscardNode}(i'') : i'' \leq i'\}| = i) \wedge \neg\text{DiscardNode}(i') \\ \text{RenumColor}(j', j) &:= (|\{\neg\text{DiscardColor}(j'') : j'' \leq j'\}| = j) \wedge \neg\text{DiscardColor}(j') \end{aligned}$$

The predicate $\text{RenumNode}(i', i)$ defines a bijection between the sets $[n-n/2k]$ and the non-discarded nodes of $[n]$. Likewise, the predicate $\text{RenumColor}(j', j)$ defines a bijection between $[(n-n/2k)-2k+1]$ and the non-discarded colors.

For each $S = \{i_1, \dots, i_k\} \in \binom{[n-n/2k]}{k}$ and $j \in [(n-n/2k)-2k+1]$, we define by extension

$$p'_{S,j} \equiv \bigvee_{i'_1, \dots, i'_k, j'} \left(\bigwedge_{t=1}^k (\text{RenumNode}(i'_t, i_t)) \wedge \text{RenumColor}(j', j) \wedge p_{\{i'_1, \dots, i'_k, j'\}} \right).$$

The Frege proof then argues that if the variables $p_{S,j}$ define a coloring, then the variables $p'_{S,j}$ define a coloring, i.e., that $\neg\text{Kneser}_k^n(\vec{p}) \rightarrow \neg\text{Kneser}_k^{n-n/2k}(\vec{p}')$. The first step for this is proving that there are at least $n/2k$ star-shaped color classes by formalizing the proofs of Lemmas 7 and 9. Those proofs were “counting” arguments: they involved counting the number of members of $\binom{[n]}{k}$ that are contained in the color classes P_ℓ . Since $\binom{[n]}{k} < n^k$, there are only polynomially many members of $\binom{[n]}{k}$. Likewise there are $< n$ color classes. The proofs of Lemmas 7 and 9 used binomial coefficients $\binom{[n']}{k'}$, but only with $n' \leq n$ and $k' \leq k$, thus the proofs only used counting for polynomial size sets. Therefore, all these counting arguments can be carried out using polynomial size Frege proofs with the techniques from [8]. From this, the fact that $\text{RenumNode}(i', i)$ and $\text{RenumColor}(j', j)$ define bijections follows easily.

After that, it is straightforward to prove that, for each $S \in \binom{[n-n/2k]}{k}$ and $j \in [(n-n/2k)-2k+1]$, the variable $p'_{S,j}$ is well-defined. In addition, a polynomial size Frege proof can prove that if $\text{Kneser}_k^n(\vec{p})$ is false, then $\text{Kneser}_k^{n-n/2k}(\vec{p}')$ is false.

This is iterated $O(\log n)$ times until fewer than $N(k, 1/2)$ nodes remain. The proof concludes with a hard-coded proof that there are no such colorings of the finitely many small Kneser graphs.

To form the quasi-polynomial size Frege proof, we unwind the definitions by extension. Each definition by extension was polynomial size; they are nested to a depth of $O(\log n)$. So the resulting Frege proof is quasi-polynomial size. \square

5. The Tucker Lemma and the Truncated Tucker Lemmas

A natural question arising from the previous sections is the possibility of giving short uniform Frege proofs of the Kneser-Lovász theorem for fixed k , namely, proofs that avoid handling finitely many base cases separately. A possible approach to this problem is formalizing the proof of Matoušek [24] in the Frege system. A significant obstacle in carrying this out is that Matoušek's proof goes through the octahedral Tucker lemma, and, as will be discussed below, naïve propositional translations of the octahedral Tucker lemma are exponential size. To overcome this, we describe two miniaturizations of the octahedral Tucker lemma, called the truncated Tucker lemmas. The truncated Tucker lemmas have polynomial size propositional translations, and are strong enough to imply the Kneser-Lovász theorem with polynomial size, constant depth Frege proofs.

Our definitions and proofs below borrow techniques and notation from Matoušek [24].

Definition 12. Let $n \geq 1$. The *octahedral ball* \mathcal{B}^n is:

$$\mathcal{B}^n := \{(A, B) : A, B \subseteq [n] \text{ and } A \cap B = \emptyset\}.$$

Definition 13. Let $n > 1$. A mapping $\lambda : \mathcal{B}^n \rightarrow \{1, \pm 2, \dots, \pm n\}$ is *antipodal* if $\lambda(\emptyset, \emptyset) = 1$, and for all other pairs $(A, B) \in \mathcal{B}^n$, $\lambda(A, B) = -\lambda(B, A)$.

Note that -1 is not in the range of λ , and (\emptyset, \emptyset) is the only member of \mathcal{B}^n that is mapped to 1 by λ .

Definition 14. Two pairs (A_1, B_1) and (A_2, B_2) in \mathcal{B}^n are *complementary* with respect to an antipodal map λ on \mathcal{B}^n if $A_1 \subseteq A_2$, $B_1 \subseteq B_2$ and $\lambda(A_1, B_1) = -\lambda(A_2, B_2)$.

Theorem 15 (Octahedral Tucker lemma). *If $\lambda : \mathcal{B}^n \rightarrow \{1, \pm 2, \dots, \pm n\}$ is antipodal, then there are two elements in \mathcal{B}^n that are complementary.*

For a proof of Theorem 15, see [24].

Definition 16. Let $1 \leq k \leq n$. The *truncated octahedral ball* $\mathcal{B}_{\leq k}^n$ is:

$$\mathcal{B}_{\leq k}^n := \{(A, B) \in \mathcal{B}^n : |A| \leq k, |B| \leq k\}.$$

We write $\binom{n}{\leq k}$ for $\{A \subseteq [n] : |A| \leq k\}$.

The octahedral Tucker lemma used the subset relation \subseteq on $[n]$ to define complementary. The truncated Tucker lemma uses an analogous partial order \preceq to define k -complementary. For $A \subseteq [n]$, let $A_{\leq k}$ denote the least k elements of A . By convention, if $|A| < k$, then $A_{\leq k} = A$.

Definition 17. Let \preceq be the partial order on sets in $\binom{n}{\leq k}$ defined by $A \preceq B$ iff $(A \cup B)_{\leq k} = B$.

Remark: Note that when $n = k$, $\mathcal{B}^n = \mathcal{B}_{\leq k}^n$, and the \preceq relation is identical to the subset relation.

Lemma 18. *The relation \preceq is a partial order with \emptyset its least element.*

Proof. It is clearly reflexive. For anti-symmetry, $A_1 \preceq A_2$ and $A_2 \preceq A_1$ imply that $A_1 = (A_1 \cup A_2)_{\leq k} = (A_2 \cup A_1)_{\leq k} = A_2$. For transitivity, suppose $A_1 \preceq A_2$ and $A_2 \preceq A_3$. Then $(A_1 \cup A_2)_{\leq k} = A_2$ and $(A_2 \cup A_3)_{\leq k} = A_3$. This implies that

$$A_3 = (A_2 \cup A_3)_{\leq k} = ((A_1 \cup A_2)_{\leq k} \cup A_3)_{\leq k} = (A_1 \cup (A_2 \cup A_3)_{\leq k})_{\leq k} = (A_1 \cup A_3)_{\leq k}.$$

Therefore $A_1 \preceq A_3$. That \emptyset is the least element is clear from the definition. \square

Definition 19. For (A_1, B_1) and (A_2, B_2) in $\mathcal{B}_{\leq k}^n$, write $(A_1, B_1) \preceq (A_2, B_2)$ when $A_1 \preceq A_2$, $B_1 \preceq B_2$, and $A_i \cap B_j = \emptyset$ for $i, j \in \{1, 2\}$. The pairs (A_1, B_1) and (A_2, B_2) are k -complementary with respect to an antipodal map λ on \mathcal{B}_k^n if $(A_1, B_1) \preceq (A_2, B_2)$ and $\lambda(A_1, B_1) = -\lambda(A_2, B_2)$.

We are ready to state the version of the truncated Tucker lemma for $\mathcal{B}_{\leq k}^n$.

Theorem 20 (Truncated Tucker lemma on $\mathcal{B}_{\leq k}^n$). *Let $n \geq k \geq 1$. If $\lambda : \mathcal{B}_{\leq k}^n \rightarrow \{1, \pm 2, \dots, \pm n\}$ is antipodal, then there are two elements in $\mathcal{B}_{\leq k}^n$ that are k -complementary.*

When $k = n$, this is equivalent to the octahedral Tucker lemma. The truncated Tucker lemma on $\mathcal{B}_{\leq k}^n$ follows from the octahedral Tucker lemma:

Proof of Theorem 20 from Theorem 15. We argue by contradiction. Suppose $\lambda : \mathcal{B}_{\leq k}^n \rightarrow \{1, \pm 2, \dots, \pm n\}$ is antipodal. We define $\lambda' : \mathcal{B}^n \rightarrow \{1, \pm 2, \dots, \pm n\}$. For $(A, B) \in \mathcal{B}^n$, define $\lambda'(A, B) = \lambda(A_{\leq k}, B_{\leq k})$. The map λ' is clearly antipodal, so by Theorem 15, there are $(A, B), (C, D)$ in \mathcal{B}^n that are complementary with respect to λ' . We claim that $(A_{\leq k}, B_{\leq k})$ and $(C_{\leq k}, D_{\leq k})$ are k -complementary with respect to λ . By definition of λ' , $\lambda(A_{\leq k}, B_{\leq k}) = -\lambda(C_{\leq k}, D_{\leq k})$, so it remains to show that $(A_{\leq k}, B_{\leq k}) \preceq (C_{\leq k}, D_{\leq k})$. Since $C \cap D = \emptyset$ and $A \subseteq C$ and $B \subseteq D$, it follows that

$$C_{\leq k} \cap D_{\leq k} = A_{\leq k} \cap D_{\leq k} = A_{\leq k} \cap B_{\leq k} = B_{\leq k} \cap C_{\leq k} = \emptyset.$$

Moreover, $A \subseteq C$ implies that $A_{\leq k} \preceq C_{\leq k}$. This is because

$$(A_{\leq k} \cup C_{\leq k})_{\leq k} = (A \cup C)_{\leq k} = C_{\leq k}.$$

The same argument shows that $B_{\leq k} \preceq D_{\leq k}$. \square

Definition 21. Let $1 < 2k \leq n$. The truncated octahedral ball \mathcal{B}_k^n is:

$$\mathcal{B}_k^n := \left\{ (A, B) : A, B \in \binom{[n]}{k} \cup \{\emptyset\}, A \cap B = \emptyset, \text{ and } (A, B) \neq (\emptyset, \emptyset) \right\}.$$

The fact that (\emptyset, \emptyset) is excluded from \mathcal{B}_k^n is only a technical convenience. Corresponding to this, the value “1” will now be omitted from the range of λ . We say that $\lambda : \mathcal{B}_k^n \rightarrow \{\pm 2k, \dots, \pm n\}$ is *antipodal* provided that $\lambda(A, B) = -\lambda(B, A)$ for all $(A, B) \in \mathcal{B}_k^n$.

Theorem 22 (Truncated Tucker lemma on \mathcal{B}_k^n). *Let $n \geq 2k > 1$. If $\lambda : \mathcal{B}_k^n \rightarrow \{\pm 2k, \dots, \pm n\}$ is antipodal, then there are two elements in \mathcal{B}_k^n that are k -complementary.*

Proof of Theorem 22 from Theorem 20. Suppose that $\lambda : \mathcal{B}_k^n \rightarrow \{\pm 2k, \dots, \pm n\}$ is antipodal; we must show it has k -complementary pairs. We extend λ to an antipodal $\lambda' : \mathcal{B}_{\leq k}^n \rightarrow \{1, \pm 2, \dots, \pm n\}$. Let “ \leq ” be any total order on $\binom{[n]}{\leq k}$ that extends \preceq . Let $(A, B) \in \mathcal{B}_{\leq k}^n$. The value of $\lambda'(A, B)$ is defined by cases:

Case 1: If $|A| < k$ and $|B| < k$, then define

$$\lambda'(A, B) = \begin{cases} 1 + |A| + |B| & \text{if } A \leq B \\ -(1 + |A| + |B|) & \text{if } B < A. \end{cases}$$

Case 2: If $\max\{|A|, |B|\} = k$ and $\min\{|A|, |B|\} < k$, then define

$$\lambda'(A, B) = \begin{cases} \lambda(A, \emptyset) & \text{if } |B| < k \\ \lambda(\emptyset, B) & \text{if } |A| < k. \end{cases}$$

Case 3: If $|A| = |B| = k$, then define $\lambda'(A, B) = \lambda(A, B)$.

The map λ' is clearly antipodal; hence by Theorem 20 there are $(A_1, B_1) \preceq (A_2, B_2)$ that are k -complementary with respect to λ' , so $\lambda'(A_1, B_1) = -\lambda'(A_2, B_2)$. We prove this gives rise to k -complementary pairs for λ . The argument splits into cases depending on how λ' assigns values to (A_1, B_1) and (A_2, B_2) .

Suppose that $\lambda'(A_1, B_1)$ is assigned by case 1, then $\lambda'(A_2, B_2)$ must also be assigned by case 1, since case 1 only assigns values to $\{1, \pm 2, \dots, \pm(2k-1)\}$, and cases 2 and 3 only assign values to $\{\pm 2k, \dots, \pm n\}$. Also, $A_1 \preceq A_2$ and $B_1 \preceq B_2$ where at least one of these precedences is proper; this implies that $|A_1| \leq |A_2|$ and $|B_1| \leq |B_2|$ where at least one of these inequalities must be proper. Thus $1 + |A_1| + |B_1| < 1 + |A_2| + |B_2|$, so $\lambda'(A_1, B_1)$ and $\lambda'(A_2, B_2)$ differ in absolute value. This contradicts the fact that (A_1, B_1) and (A_2, B_2) are k -complementary w.r.t. λ' . Thus it is impossible that both $\lambda'(A_1, B_1)$ and $\lambda'(A_2, B_2)$ are assigned by case 1.

Suppose $\lambda'(A_1, B_1)$ and $\lambda'(A_2, B_2)$ are both assigned by case 2. Without loss of generality $|B_1| < k$, which implies $|A_1| = |A_2| = k$ and $|B_2| < k$. This implies that $\lambda(A_1, \emptyset) = -\lambda(A_2, \emptyset)$. But $(A_1, \emptyset) \preceq (A_2, \emptyset)$, so these form a k -complementary pair for λ .

Suppose $\lambda'(A_1, B_1)$ is assigned by case 2 and $\lambda'(A_2, B_2)$ is assigned by case 3. Without loss of generality $|B_1| < k$. This implies that $\lambda(A_1, \emptyset) = -\lambda(A_2, B_2)$. But $(A_1, \emptyset) \preceq (A_2, B_2)$, so these form a k -complementary pair for λ .

Suppose $\lambda'(A_1, B_1)$ and $\lambda'(A_2, B_2)$ are both assigned by case 3. Thus $\lambda(A_1, B_1) = -\lambda(A_2, B_2)$, so these form a k -complementary pair for λ .

Suppose $\lambda'(A_1, B_1)$ is assigned by case 3 and $\lambda'(A_2, B_2)$ is assigned by case 2. This is impossible because $|A_1| = |B_1| = k$, and $A_1 \preceq A_2$, $B_1 \preceq B_2$, so $|B_1| = |B_2| = k$. \square

For fixed parameter k , the two truncated Tucker lemmas have polynomial size propositional translations. We will only describe the translation of the truncated Tucker lemma on \mathcal{B}_k^n . A similar translation works for the truncated Tucker lemma on $\mathcal{B}_{\leq k}^n$. For each $(A, B) \in \mathcal{B}_k^n$, and for each $i \in \{\pm 2k, \dots, \pm n\}$, let $p_{A,B,i}$ be a propositional variable with the intended meaning that $p_{A,B,i}$ is true when $\lambda(A, B) = i$. The following formula $\text{Ant}(\vec{p})$ states that the map is total and antipodal:

$$\bigwedge_{(A,B) \in \mathcal{B}_k^n} \bigvee_{i \in \{\pm 2k, \dots, \pm n\}} (p_{A,B,i} \wedge p_{B,A,-i}).$$

The following formula $\text{Comp}(\vec{p})$ states that there exists two elements in \mathcal{B}_k^n that are k -complementary:

$$\bigvee_{\substack{(A_1, B_1), (A_2, B_2) \in \mathcal{B}_k^n, \\ (A_1, B_1) \preceq (A_2, B_2) \\ i \in \{\pm 2k, \dots, \pm n\}}} (p_{A_1, B_1, i} \wedge p_{A_2, B_2, -i}).$$

The truncated Tucker tautology Tucker_k^n is defined to be $\text{Ant}(\vec{p}) \rightarrow \text{Comp}(\vec{p})$. (We could add an additional hypothesis, that for each A, B there is at most one i such that $p_{A,B,i}$, but this is not needed for the Tucker tautologies to be valid.) There are $< n^{2k}$ members (A, B) in \mathcal{B}_k^n . Hence, for fixed k , there are only polynomially many variables $p_{A,B,i}$, and the truncated Tucker tautologies have size polynomially bounded by n . On the other hand, the propositional translation of the octahedral Tucker lemma requires an exponential number of propositional variables in n , since the cardinality of \mathcal{B}^n is exponential in n .

The proof of Theorem 22 from Theorem 20 can be readily translated into polynomial size Frege proofs. That is, if propositional translations of the truncated Tucker lemma on $\mathcal{B}_{\leq k}^n$ are given as hypotheses, there are polynomial size Frege proofs of the polynomial translations of the truncated Tucker lemma on \mathcal{B}_k^n . Section 5.1 will prove a converse: the truncated Tucker lemma on $\mathcal{B}_{\leq k}^n$ follows from the truncated Tucker lemma on \mathcal{B}_k^{n+2k-1} by polynomial size Frege proofs.

We next show that the Kneser-Lovász theorem (Theorem 1) follows from the truncated Tucker lemma on \mathcal{B}_k^n .

Proof of Theorem 1 from Theorem 22. Suppose for sake of contradiction that $c : \binom{n}{k} \rightarrow \{2k, \dots, n\}$ is an $(n-2k+1)$ -coloring of $\binom{n}{k}$. Let \leq be a total order on $\binom{n}{k} \cup \{\emptyset\}$ that refines the partial order \preceq . Let $(A, B) \in \mathcal{B}_k^n$. Define $\lambda(A, B)$ as

follows:

$$\lambda(A, B) = \begin{cases} c(A) & \text{if } A > B \\ -c(B) & \text{if } B > A \end{cases}$$

The map λ is clearly antipodal, so by Theorem 22, there is a pair $(A_1, B_1) \preceq (A_2, B_2) \in \mathcal{B}_k^n$ that is k -complementary. Since λ must assign (A_1, B_1) and (A_2, B_2) opposite signs, it must be that either $A_1 < B_1 \leq B_2 < A_2$ or $B_1 < A_1 \leq A_2 < B_2$. In the former case, $c(B_1) = c(A_2)$ and in the latter case $c(A_1) = c(B_2)$. Since $B_1 \cap A_2 = A_1 \cap B_2 = \emptyset$, in either case we have a contradiction. \square

The above proof of the Kneser-Lovász theorem from the truncated Tucker lemma can be readily translated into polynomial size constant depth Frege proofs.

Question 23. *Do the propositional translations of the truncated Tucker lemma have short (extended) Frege proofs?*

5.1. Equivalence Between the Truncated Tucker Lemmas

Theorem 24. *The truncated Tucker lemma on \mathcal{B}_k^n implies the truncated Tucker lemma on $\mathcal{B}_{\leq k}^{n-2k+1}$.*

Proof. Let $1 < 2k \leq n$. Suppose that $\lambda : \mathcal{B}_{\leq k}^{n-2k+1} \rightarrow \{1, \pm 2, \dots, \pm(n-2k+1)\}$ is an antipodal map. By renaming the range elements, we can instead write $\lambda : \mathcal{B}_{\leq k}^{n-2k+1} \rightarrow \{1, \pm 2k, \dots, \pm(n-1)\}$. We will define $\lambda' : \mathcal{B}_k^n \rightarrow \{\pm 2k, \dots, \pm n\}$ as follows: For $(A, B) \in \mathcal{B}_k^n$,

$$\lambda'(A, B) = \begin{cases} \lambda(A^*, B^*) & \text{if } A \neq \emptyset \text{ and } B \neq \emptyset \\ n & \text{if } A = \emptyset \\ -n & \text{if } B = \emptyset \end{cases}$$

where $A^* = \{a \in A : a \leq n - 2k + 1\}$. For $(A, B) \in \mathcal{B}_k^n$, we clearly have $(A^*, B^*) \in \mathcal{B}_{\leq k}^{n-2k+1}$. We also claim that $\lambda'(A, B)$ is never equal to 1. To prove this, suppose $\lambda'(A, B) = 1$. By the definition of λ' , both A and B are nonempty. Thus $\lambda(A^*, B^*) = 1$ and consequently $A^* = B^* = \emptyset$. This means that A and B are both subsets of $\{n-2k+2, \dots, n\}$, a set of cardinality $2k-1$. But this contradicts $A \cap B = \emptyset$ and $|A| = |B| = k$.

The map λ' is clearly antipodal by definition. By the truncated Tucker lemma on \mathcal{B}_k^n , there are pairs $(A_1, B_1) \preceq (A_2, B_2) \in \mathcal{B}_k^n$ such that $\lambda'(A_1, B_1) = -\lambda'(A_2, B_2)$. We claim that $\lambda(A_1, B_1) \neq n$. Otherwise, $\lambda(A_2, B_2) = -n$, so $A_1 = \emptyset$ and $B_2 = \emptyset$, and this contradicts $(A_1, B_1) \preceq (A_2, B_2)$. Similarly, $\lambda(A_1, B_1) \neq -n$. It follows that all four sets A_1, B_1, A_2, B_2 are nonempty. Therefore, by the choice of (A_1, B_1) and (A_2, B_2) ,

$$\lambda(A_1^*, B_1^*) = -\lambda(A_2^*, B_2^*).$$

We now claim that $(A_1^*, B_1^*) \preceq (A_2^*, B_2^*)$. Since $A_1 \cap B_2 = \emptyset$ and $A_2 \cap B_1 = \emptyset$, we have $A_1^* \cap B_2^* = \emptyset$ and $A_2^* \cap B_1^* = \emptyset$. Also, since $A_1 \preceq A_2$,

$$(A_1 \cup A_2)_{\leq k} = A_2$$

From this we obtain

$$(A_1^* \cup A_2^*)_{\leq k} = ((A_1 \cup A_2)_{\leq k})^* = A_2^*.$$

Thus $A_1^* \preceq A_2^*$. The same argument shows $B_1^* \preceq B_2^*$. This establishes that (A_1^*, B_1^*) and (A_2^*, B_2^*) are k -complementary with respect to λ . \square

Since the proofs of the equivalence of the two truncated Tucker lemmas can be translated into polynomial size Frege proofs, we have established:

Corollary 25. *The propositional translations of the truncated Tucker lemma on \mathcal{B}_k^n have (quasi-)polynomial size Frege proofs if and only if the same holds for the truncated Tucker lemma on $\mathcal{B}_{\leq k}^n$.*

6. Short $e\mathcal{F}$ Proofs of the Truncated Tucker Lemma, $k = 1$ Case

In this section we prove the $k = 1$ case of the truncated Tucker lemma. The argument is readily formalizable as polynomial size extended Frege proofs. Note that when $k = 1$ the two versions of the truncated Tucker lemma are equivalent.

Recall the partial order \preceq of Definition 17. When $k = 1$, this partial order is a total order where $\{i\} \preceq \{j\}$ iff $i \geq j$. Thus,

$$\emptyset \preceq \{n\} \preceq \{n-1\} \preceq \dots \preceq \{2\} \preceq \{1\}$$

is a complete description of \preceq on $\binom{[n]}{1}$.

Theorem 26. *The $k = 1$ case of the truncated Tucker lemma, Tucker_1^n , has polynomial size extended Frege proofs.*

The polynomial size extended Frege proofs of the $k = 1$ case of the truncated Tucker lemma are formed by formalizing the argument of Lemma 27 below.

Lemma 27. *Let $\lambda : \mathcal{B}_1^n \rightarrow \{\pm 2, \dots, \pm n\}$ be an antipodal map with no 1-complementary pairs. Then there is an antipodal map $\lambda' : \mathcal{B}_1^{n-1} \rightarrow \{\pm 2, \dots, \pm(n-1)\}$ with no 1-complementary pairs.*

Proof. Let $\lambda : \mathcal{B}_1^n \rightarrow \{\pm 2, \dots, \pm n\}$ be an antipodal map with no 1-complementary pairs, and let $\ell = \lambda(\{n\}, \emptyset)$. We will define an antipodal map $\lambda' : \mathcal{B}_1^{n-1} \rightarrow \{\pm 2, \dots, \pm n\} \setminus \{\pm \ell\}$. Let $(A, B) \in \mathcal{B}_1^{n-1}$. The value $\lambda'(A, B)$ will be defined by cases.

Case 1: If $(A, B) \in \mathcal{B}_1^{n-1}$ with $|A| = |B| = 1$, then $\lambda'(A, B) = \lambda(A, B)$.

Case 2: If $(A, \emptyset) \in \mathcal{B}_1^{n-1}$, then $\lambda'(A, \emptyset)$ is defined by cases:

Case 2a: If $\ell \notin \{\lambda(X, \emptyset) : \{n-1\} \preceq X \preceq A\}$, then define $\lambda'(A, \emptyset)$ to be $\lambda(A, \emptyset)$.

Case 2b: If case 2a does not apply, then define $\lambda'(A, \emptyset)$ to be $\lambda(A, \{n\})$.

Case 3: If $(\emptyset, B) \in \mathcal{B}_1^{n-1}$, then $\lambda'(\emptyset, B)$ is defined to be $-\lambda'(B, \emptyset)$, where $\lambda'(B, \emptyset)$ has already been defined by case 2.

The map λ' is antipodal because λ is.

Claim 28. *The map λ' never maps to ℓ or $-\ell$.*

The argument splits into cases.

- Suppose $(A, B) \in \mathcal{B}_1^{n-1}$, with $|A| = |B| = 1$. Then $\lambda'(A, B) = \lambda(A, B)$. Since $|A| = 1$, $\{n\} \preceq A$, and since $B \in \binom{[n-1]}{1}$, it follows that $\{n\} \cap B = \emptyset$. Additionally $\emptyset \preceq B$, and $\emptyset \cap A = \emptyset$. Therefore $(\{n\}, \emptyset) \preceq (A, B)$. Since λ has no 1-complementary pairs, and $\lambda(\{n\}, \emptyset) = \ell$, it follows that $\lambda(A, B) \neq -\ell$. Therefore $\lambda'(A, B) \neq -\ell$. Because λ' is antipodal, this also proves $\lambda'(A, B) \neq \ell$.
- Suppose $(A, \emptyset) \in \mathcal{B}_1^{n-1}$, and $\lambda'(A, \emptyset)$ is assigned by case 2a. For case 2a to apply, it must be that $\lambda(A, \emptyset) \neq \ell$. Furthermore, $\lambda(\{n\}, \emptyset) = \ell$, $(\{n\}, \emptyset) \preceq (A, \emptyset)$, and the fact that λ has no 1-complementary pairs imply that $\lambda(A, \emptyset) \neq -\ell$. Therefore, $\lambda'(A, \emptyset) = \lambda(A, \emptyset) \neq \pm\ell$.
- Suppose $(A, \emptyset) \in \mathcal{B}_1^{n-1}$, and $\lambda'(A, \emptyset)$ is assigned by case 2b. This implies that there is some $X \in \binom{[n-1]}{1}$ with $\{n-1\} \preceq X \preceq A$ such that $\lambda(X, \emptyset) = \ell$. Note that $\{n-1\} \preceq X$ implies that $\{n\} \cap X = \emptyset$. Since $(X, \emptyset) \preceq (A, \{n\})$, it follows that $\lambda(A, \{n\}) \neq -\ell$. Since $\lambda(\emptyset, \{n\}) = -\ell$ and $(\emptyset, \{n\}) \preceq (A, \{n\})$ it follows that $\lambda(A, \{n\}) \neq \ell$. Thus $\lambda'(A, \emptyset) = \lambda(A, \{n\}) \neq \pm\ell$.
- Suppose $(\emptyset, B) \in \mathcal{B}_1^{n-1}$. Then $\lambda'(\emptyset, B) = -\lambda'(B, \emptyset)$, and we have shown above that $\lambda'(B, \emptyset) \neq \pm\ell$.

This completes the proof of Claim 28.

Claim 29. *The map λ' has no 1-complementary pairs.*

We show the contrapositive. The argument splits into cases.

- Suppose $(A_1, B_1) \preceq (A_2, B_2) \in \mathcal{B}_1^{n-1}$ with $|A_1| = |B_1| = |A_2| = |B_2| = 1$. Then $\lambda'(A_1, B_1)$ and $\lambda'(A_2, B_2)$ both are assigned by case 1. Thus,

$$\lambda(A_1, B_1) = \lambda'(A_1, B_1) = -\lambda'(A_2, B_2) = -\lambda(A_2, B_2)$$

Therefore λ has a 1-complementary pair.

- Suppose $(A_1, \emptyset) \preceq (A_2, B_2) \in \mathcal{B}_1^{n-1}$, with $\lambda'(A_1, \emptyset)$ assigned by case 2a and $\lambda'(A_2, B_2)$ assigned by case 1. So $\lambda(A_1, \emptyset) = -\lambda(A_2, B_2)$. Thus λ has a 1-complementary pair.

- Suppose $(A_1, \emptyset) \preceq (A_2, B_2) \in \mathcal{B}_1^{n-1}$, with $\lambda'(A_1, \emptyset)$ assigned by case 2b and $\lambda'(A_2, B_2)$ assigned by case 1. So $\lambda(A_1, \{n\}) = -\lambda(A_2, B_2)$. Since $(A_1, \{n\}) \preceq (A_2, B_2)$, it follows that λ has a 1-complementary pair.
- Suppose $(A_1, \emptyset) \preceq (A_2, \emptyset) \in \mathcal{B}_1^{n-1}$, with $\lambda'(A_1, \emptyset)$ and $\lambda'(A_2, \emptyset)$ both assigned by case 2a. So then $\lambda(A_1, \emptyset) = -\lambda(A_2, \emptyset)$, hence λ has a 1-complementary pair.
- Suppose $(A_1, \emptyset) \preceq (A_2, \emptyset) \in \mathcal{B}_1^{n-1}$, with $\lambda'(A_1, \emptyset)$ and $\lambda'(A_2, \emptyset)$ both assigned by case 2b. So then $\lambda(A_1, \{n\}) = -\lambda(A_2, \{n\})$, hence λ has a 1-complementary pair.
- Suppose $(A_1, \emptyset) \preceq (A_2, \emptyset) \in \mathcal{B}_1^{n-1}$, with $\lambda'(A_1, \emptyset)$ assigned by case 2a and $\lambda'(A_2, \emptyset)$ assigned by case 2b. Thus,

$$\lambda(A_1, \emptyset) = \lambda'(A_1, B_1) = -\lambda'(A_2, B_2) = -\lambda(A_2, \{n\})$$

and since $(A_1, \emptyset) \preceq (A_2, \{n\})$, it follows that λ has a 1-complementary pair.

- Suppose $(A_1, B_1) \preceq (A_2, \emptyset) \in \mathcal{B}_1^{n-1}$ where $|A_1| = |B_1| = 1$. This is impossible, because $B_1 \preceq \emptyset$, and no set of cardinality 1 precedes the emptyset under the partial order \preceq .
- Suppose $(A_1, \emptyset) \preceq (A_2, \emptyset) \in \mathcal{B}_1^{n-1}$, and $\lambda'(A_1, \emptyset)$ is assigned by case 2b and $\lambda'(A_2, \emptyset)$ is assigned by case 2a. Then there exists an $X \in \binom{[n-1]}{1}$ such that $\{n-1\} \preceq X \preceq A_1$ and $\lambda(X, \emptyset) = \ell$. Since $A_1 \preceq A_2$, it follows that $\{n-1\} \preceq X \preceq A_2$. This implies that $\lambda'(A_2, \emptyset)$ is not assigned by case 2a, so this case is impossible.
- Suppose $(A_1, \emptyset) \preceq (\emptyset, B_2) \in \mathcal{B}_1^{n-1}$. This is impossible, because $A_1 \preceq \emptyset$ implies that $A_1 = \emptyset$, but $(\emptyset, \emptyset) \notin \mathcal{B}_1^{n-1}$.
- The remaining cases involving case 3 of the definition of λ' follow from above, using the fact that if $(A_1, B_1) \preceq (A_2, B_2)$ form a 1-complementary pair, then $(B_1, A_1) \preceq (B_2, A_2)$ also form a 1-complementary pair.

This completes the proof of Claim 29. Claims 28 and 29 suffice to prove Lemma 27. \square

We are now ready to sketch the proof of polynomial size extended Frege proofs of Tucker_1^n .

Proof of Theorem 26. To prove $\text{Tucker}_1^n(\vec{p})$, where \vec{p} is a set of propositional variables encoding a map λ , we introduce by extension new variables \vec{p}' to encode λ' as in Lemma 27. It is straightforward to see that the definition of λ' from λ can be carried out by polynomial size formulas. Furthermore, it is straightforward to argue that there are polynomial size proofs of $\neg \text{Tucker}_1^n(\vec{p}) \rightarrow \neg \text{Tucker}_1^{n-1}(\vec{p}')$ by formalizing the argument of Lemma 27. This process is

repeated, introducing new propositional variables each round, until the proof reaches $\neg\text{Tucker}_1^2(\vec{p}'')$. From here, the proof concludes with a constant size proof of $\text{Tucker}_1^2(\vec{p}'')$. \square

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