Discrepancy after adding a single set

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Abstract

We show that the hereditary discrepancy of a hypergraph $\mathcal{F}$ on n points increases by a factor of at most $O(\log n)$ when one adds a new edge to $\mathcal{F}$.

Let X be a set of n points. We say that a hypergraph $\mathcal{F}$ on X has discrepancy h if h is the smallest integer satisfying the following: There is a coloring $\chi: X \to \{-1,+1\}$ such that for every edge $S \in \mathcal{F}$, $|\chi(S)| \le h$, where we write $\chi(S)$ for $\sum_{x\in S}\chi(x)$.

The hereditary discrepancy of $\mathcal{F}$ is the maximum discrepancy of any restriction of $\mathcal{F}$ to a subset $Y \subseteq X$. Discrepancy and hereditary discrepancy are important notions in combinatorics and discrete geometry; for more information we refer, e.g., to [1] or [2]. Throughout the note, the asymptotic notation is used under the assumption that $n \to \infty$. All logarithms have natural base. We denote by $\mathrm{disc}(\mathcal{F})$ and $\mathrm{herdisc}(\mathcal{F})$ the discrepancy and the hereditary discrepancy of $\mathcal{F}$, respectively.

The following question is a folklore in discrepancy theory (as far as we could find out, it was first asked by V. Sós some years ago): Given a hypergraph $\mathcal{F}$, is it true that the hereditary discrepancy of $\mathcal{F}$ increases by at most a constant factor if one adds a new edge to $\mathcal{F}$?

As far as we know, there is no published result on this problem, although a polynomial factor can be proved by various arguments. In this note, we prove that adding one edge increases the hereditary discrepancy of $\mathcal{F}$ by a multiplicative factor of at most $O(\log n)$.

Theorem 1 *Let X be an n-point set and let $\mathcal{F} \subseteq 2^X$ satisfy* $\mathrm{herdisc}(\mathcal{F}) \leq h$. *Then* $\mathrm{disc}(\mathcal{F} \cup \{X\}) = O(h \log n)$.

The following consequence is immediate from the definition of hereditary discrepancy:

Corollary 2 *Let X be an n-point set and let $\mathcal{F} \subseteq 2^X$ satisfy* $\mathrm{herdisc}(\mathcal{F}) \leq h$. *Then for any subset X' of X, we have* $\mathrm{herdisc}(\mathcal{F} \cup \{X'\}) = O(h \log n)$.

Proof of Theorem 1. For each set $A \in 2^X$, let $\chi_A\colon A \to \{-1, +1\}$ witness $\mathrm{disc}(\mathcal{F}|_A) \leq h$. Define two colorings χ'_A and χ''_A of X by

$$\chi'_A(x) = \begin{cases} \chi_A(x) & \text{for } x \in A \\ \chi_{X\setminus A}(x) & \text{for } x \in X \setminus A \end{cases} \qquad \chi''_A(x) = \begin{cases} -\chi_A(x) & \text{for } x \in A \\ \chi_{X\setminus A}(x) & \text{for } x \in X \setminus A. \end{cases}$$

Let $\mathcal{C} = \{\chi'_A, \chi''_A : A \in 2^X\}$. Label each pair $\{\chi_1, \chi_2\}$ of distinct colorings in $\mathcal{C}$ by the set $\{x \in X : \chi_1(x) \neq \chi_2(x)\}$. Since the pair $\{\chi'_A, \chi''_A\}$ is labeled by A, there are at least 2^n distinct pairs, and so $|\mathcal{C}| \geq 2^{n/2}$.

Divide the colorings in $\mathcal{C}$ into at most n classes according to the value of $\chi(X)$, and let $\mathcal{C}_1$ be a class with $|\mathcal{C}_1| \geq \frac{1}{n}|\mathcal{C}| \geq 2^{n/2}/n$. The rest is as in the proof of Beck's partial coloring lemma (see, e.g., [1], Lemma 4.13). Since $\mathcal{C}_1$ is exponentially large, it contains two colorings χ_1, χ_2 differing in at least cn points, for a suitable positive constant $c > 0$. We form the partial coloring $\chi = \frac{1}{2}(\chi_1 - \chi_2)\colon X \to \{-1, 0, +1\}$. We have $\chi(X) = 0$, $|\chi(S)| \leq 2h$ for all $S \in \mathcal{F}$, and at least cn points of X are colored (meaning that they receive $+1$ or -1). Next, we restrict $\mathcal{F}$ to the subset $X_1 \subset X$ that received 0 under χ and we repeat the same argument, etc. Iterating $O(\log n)$ times, all points are colored, and the total discrepancy is $O(h \log n)$. $\square$

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References

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[2] J. Spencer. *Ten lectures on the probabilistic method.* CBMS-NSF. SIAM, Philadelphia, PA, 1987.