Tilted Sperner families

Leader, Imre; Long, Eoin

DOI:
10.1016/j.dam.2012.02.024

Citation for published version (Harvard):
Leader, I & Long, E 2014, 'Tilted Sperner families', *Discrete Applied Mathematics*, vol. 163, no. 2, pp. 194-198.
https://doi.org/10.1016/j.dam.2012.02.024

Discrete Applied Mathematics 163 (2014) 194–198

Contents lists available at ScienceDirect

Discrete Applied Mathematics

journal homepage: www.elsevier.com/locate/dam

Tilted Sperner families

Imre Leader *, Eoin Long

Department of Pure Mathematics and Mathematical Statistics, Centre for Mathematical Sciences, Cambridge CB3 0WB, United Kingdom

ARTICLE INFO

Article history:
Received 25 January 2011
Accepted 22 February 2012
Available online 7 April 2012

Keywords:
Extremal combinatorics
Sperner families

ABSTRACT

Let $\mathcal{A}$ be a family of subsets of an n-set such that $\mathcal{A}$ does not contain distinct sets A and B with $|A \setminus B| = 2|B \setminus A|$. How large can $\mathcal{A}$ be? Our aim in this note is to determine the maximum size of such an $\mathcal{A}$. This answers a question of Kalai. We also give some related results and conjectures.

1. Introduction

A set system $\mathcal{A} \subseteq \mathcal{P}[n] = \mathcal{P}(\{1, \ldots, n\})$ is said to be an *antichain* or *Sperner family* if $A \not\subset B$ for all distinct $A, B \in \mathcal{A}$. Sperner's theorem [5] says that any antichain $\mathcal{A}$ has size at most $\binom{n}{\lfloor n/2 \rfloor}$. (See [2] for general background.)

Kalai [3] noted that the antichain condition may be restated as: $\mathcal{A}$ does not contain A and B such that, in the subcube of the n-cube spanned by A and B, they are the top and bottom points. He asked what happens if we 'tilt' this condition. For example, suppose that we instead forbid A, B such that A is $1/3$ of the way up the subcube spanned by A and B? Equivalently, $\mathcal{A}$ cannot contain two sets A and B with $|A \setminus B| = 2|B \setminus A|$.

An obvious example of such a system is any level set $[n]^{(i)} = \{A \subset [n] : |A| = i\}$. Thus we may certainly achieve size $\binom{n}{\lfloor n/2 \rfloor}$. The system $[n]^{(\lfloor n/2 \rfloor)}$ is not maximal, as we may for example add to it all sets of size $\lfloor n/4 \rfloor - 1$—but that is a rather small improvement. Kalai [3] asked if, as for Sperner families, it is still true that our family $\mathcal{A}$ must have size $o(2^n)$.

Our aim in this note is to verify this. We show that the middle layer is asymptotically best, in the sense that the maximum size of such a family is $(1 + o(1))\binom{n}{\lfloor n/2 \rfloor}$. We also find the exact extremal system, for n even and sufficiently large. We give similar results for any particular 'forbidden ratio' in the subcube spanned.

What happens if, instead of forbidding a particular ratio, we instead forbid an absolute distance from the bottom point? For example, for distance 1 this would correspond to the following: our set system $\mathcal{A}$ must not contain sets A and B with $|A \setminus B| = 1$. How large can $\mathcal{A}$ be?

Here the situation is rather different, as for example one cannot take an entire level. We give a construction that has size about $\frac{1}{n}\binom{n}{\lfloor n/2 \rfloor}$, which is about (a constant fraction of) $1/n^{3/2}$ of the whole cube. But we are not able to show that this is optimal: the best upper bound that we are able to give is $2^n/n$. However, if we strengthen the condition to $\mathcal{A}$ not having A and B with $|A \setminus B| \le 1$ then we are able to show that the greatest family has size $\frac{1}{n}\binom{n}{\lfloor n/2 \rfloor}$, up to a multiplicative constant.

* Correspondence to: Department of Pure Mathematics and Mathematical Statistics, University of Cambridge, Cambridge, United Kingdom. Fax: +44 1223337920.

E-mail addresses: I.Leader@dpmms.cam.ac.uk (I. Leader), E.P.Long@dpmms.cam.ac.uk (E. Long).

0166-218X/$ – see front matter
doi:10.1016/j.dam.2012.02.024

2. Forbidding a fixed ratio

In this section we consider the problem of finding the maximum size of a family $\mathcal{A}$ of subsets of $[n]$ which satisfies $p|A\setminus B| \neq q|B\setminus A|$ for all $A, B \in \mathcal{A}$ where $p:q$ is a fixed ratio. Initially we will focus on the first non-trivial case 1:2 (note that 1:1 is trivial as then the condition just forbids two sets of the same size in $\mathcal{A}$) and then at the end of the section we extend these results to any given ratio.

As mentioned in the Introduction, for the ratio 1:2 we actually obtain the extremal family when n is even and sufficiently large. This family, which we will denote by $\mathcal{B}_0$, is a union of level sets: $\mathcal{B}_0 = \cup_{i\in I}[n]^{(i)}$. Here the set I is defined as follows: $I = \{a_i : i \geq 0\} \cup \{b_i : i \geq 0\}$, where $a_0 = b_0 = \frac{n}{2}$ and a_i and b_i are defined inductively by taking $a_i = \lceil \frac{a_{i-1}}{2} \rceil - 1$ and $b_i = \lfloor \frac{b_{i-1}+n}{2} \rfloor + 1$ for all i. For example, if $n = 2^k$ then $I = \{2^{k-1}\} \cup \{2^i - 1 : 0 \leq i \leq k-1\} \cup \{2^k - 2^i + 1 : 0 \leq i \leq k-1\}$. Noting that for any sets A and B with either (i) $|A| = l$ where $l < \frac{n}{2}$ and $|B| > 2l$ or (ii) $|A| = l$ where $l > \frac{n}{2}$ and $|B| < 2l - n$ we have $|A\setminus B| \neq 2|B\setminus A|$, we see that $\mathcal{B}_0$ satisfies the required condition. Our main result is the following.

Theorem 1. *Suppose $\mathcal{A}$ is a set system on ground set $[n]$ such that $|A\setminus B| \neq 2|B\setminus A|$ for all distinct $A, B \in \mathcal{A}$. Then $|\mathcal{A}| \leq (1+o(1))\binom{n}{\lfloor n/2\rfloor}$. Furthermore, if n is even and sufficiently large then $|\mathcal{A}| \leq |\mathcal{B}_0|$, with equality if and only if $\mathcal{A} = \mathcal{B}_0$.*

The main step in the proof of Theorem 1 is given by the following lemma. The proof is a Katona-type (see [4]) averaging argument.

Lemma 2. *Let $\mathcal{A}$ be a set system on $[n]$ such that $|A\setminus B| \neq 2|B\setminus A|$ for all distinct $A, B \in \mathcal{A}$. Then*

$$\sum_{j=l}^{2l} \frac{|\mathcal{A}_j|}{\binom{n}{j}} \leq 1$$

for all $l \leq \frac{n}{3}$ and

$$\sum_{j=2k-n}^{k} \frac{|\mathcal{A}_j|}{\binom{n}{j}} \leq 1$$

for all $k \geq \frac{2n}{3}$, where $\mathcal{A}_j = \mathcal{A} \cap [n]^{(j)}$.

Proof. We only prove the first inequality, as the proof of the second is identical. Pick a random ordering of $[n]$ which we denote by $(a_1, a_2, \ldots, a_{\lceil \frac{2n}{3}\rceil}, b_1, \ldots, b_{\lfloor \frac{n}{3}\rfloor})$. Given this ordering, let $C_i = \{a_j : j \in [2i]\} \cup \{b_k : k \in [i+1, l]\}$ and let $\mathcal{C} = \{C_i : i \in [0, l]\}$. Consider the random variable $X = |\mathcal{A} \cap \mathcal{C}|$. Since each set $B \in [n]^{(i)}$ is equally likely to be C_{i-l} we have $\mathbb{P}[B \in \mathcal{C}] = \frac{1}{\binom{n}{i}}$. Thus by linearity of expectation we have

$$\mathbb{E}(X) = \sum_{i=l}^{2l} \frac{|\mathcal{A}_i|}{\binom{n}{i}}. \tag{1}$$

On the other hand, given any C_i, C_j with $i < j$ we have $|C_i \setminus C_j| = 2|C_j \setminus C_i|$ and so $\mathcal{A}$ can contain at most one of these sets. This gives $\mathbb{E}(X) \leq 1$. Together with (1) this gives the claimed inequality

$$\sum_{i=l}^{2l} \frac{|A_i|}{\binom{n}{i}} \leq 1. \quad \square$$

Proof of Theorem 1. We first show $|\mathcal{A}| \leq (1+o(1))\binom{n}{\lfloor n/2\rfloor}$. By standard estimates (see e.g. Appendix A of [1]) we have $|[n]^{(\leq \alpha n)} \cup [n]^{(\geq (1-\alpha)n)}| = o(\binom{n}{\lfloor n/2\rfloor})$ for any fixed $\alpha \in [0, \frac{1}{2})$, so it suffices to show that $|\bigcup_{i=\frac{2n}{5}}^{\frac{3n}{5}} \mathcal{A}_i| \leq \binom{n}{\frac{n}{2}}$. But this follows immediately from Lemma 2 by taking $l = \lfloor \frac{n}{3} \rfloor$.

We now prove the extremal part of the claim in Theorem 1. We first show that the maximum of $f(x) = \sum_{i=0}^{n} x_i$ subject to the inequalities

$$\sum_{j=l}^{2l} \frac{x_j}{\binom{n}{j}} \leq 1, \quad l \in \left\{0, 1, \ldots, \left\lfloor \frac{n}{3} \right\rfloor\right\} \tag{2}$$

and

$$\sum_{j=2k-n}^{k} \frac{x_j}{\binom{n}{j}} \leq 1, \quad k \in \left\{\left\lceil \frac{2n}{3} \right\rceil, \ldots, n\right\} \tag{3}$$

from Lemma 2 occurs when $x_{n/2} = \binom{n}{\frac{n}{2}}$. Indeed, suppose otherwise. At least one of these inequalities involving $x_{n/2}$ must occur with equality, as otherwise we can increase $x_{n/2}$ slightly, increase the value of $f(x)$ and still satisfy (2) and (3). Pick $j > \frac{n}{2}$ as small as possible such that $x_j > 0$. Let $y_{n/2} = x_{n/2} + \epsilon\binom{n}{n/2}$, $y_j = x_j - \epsilon\binom{n}{j}$ and $y_i = x_i$ for all other i. As $f(y) > f(x)$ one of the (2) or (3) must fail. If ϵ is sufficiently small only the inequalities involving $y_{n/2}$ and not y_j can be violated. Choose $k < n/2$ maximal such that $y_k > 0$ and y_k does not occur in any inequality involving y_j. Note that we must have $j - k \geq \frac{n}{4}$. Decrease y_k by $\epsilon\binom{n}{k}$. Since the only increased variable $y_{n/2}$ always occurs with one of y_j or y_k, it follows that $y = (y_0, \ldots, y_n)$ satisfies (2) and (3).

We claim that $f(y) > f(x)$. Indeed, we must have either $|j - \frac{n}{2}| \geq \frac{n}{8}$ or $|k - \frac{n}{2}| \geq \frac{n}{8}$. Without loss of generality assume that $|k - \frac{n}{2}| \geq \frac{n}{8}$. Then since $\binom{n}{n/2} > \binom{n}{(n/2)+1} + \binom{n}{3n/8}$ for sufficiently large n we have

$$f(y) = f(x) + \epsilon\binom{n}{n/2} - \epsilon\binom{n}{j} - \epsilon\binom{n}{k} > f(x) + \epsilon\binom{n}{n/2} - \epsilon\binom{n}{(n/2)+1} - \epsilon\binom{n}{3n/8} > f(x).$$

Therefore we must have $x_{n/2} = \binom{n}{n/2}$, as claimed.

Now, by the inequalities (2) and (3) we have $x_j = 0$ for all $\frac{n}{4} \leq j \leq \frac{3n}{4}$ with $j \neq \frac{n}{2}$. From here it is easy to see by a weight transfer argument that $f(x)$ has a unique maximum when $x_i = \binom{n}{i}$ for $i \in I$ and $x_i = 0$ otherwise. For a set system $\mathcal{A}$ these values of $x_i = |\mathcal{A}_i|$ can only be achieved if $\mathcal{A} = \mathcal{B}_0$, as claimed. $\square$

We remark that the statement of Theorem 1 does not hold for all even n, as can be seen for example by taking $n = 4$ and $\mathcal{A} = \mathcal{P}[n] \setminus [n]^{(2)}$.

We now extend Theorem 1 from the ratio $1 : 2$ to any given ratio $p : q$. Let $p : q$ be in its lowest terms and $p < q$. If $A \in [n]^{(i+a)}$ and $B \in [n]^{(i)}$ satisfy $p|A \setminus B| = q|B \setminus A|$ then we have $p(a + b) = q(b)$ where $b = |B \setminus A|$. But then $pa = (q - p)b$ and since p and q are coprime we must have that $(q - p)|a$. Therefore any family $\mathcal{A} = \bigcup_{i\in I}[n]^{(i)}$, where I is an interval of length $q - p$, satisfies $p|A \setminus B| \neq q|B \setminus A|$ for all $A, B \in \mathcal{A}$. Taking $\lfloor \frac{n}{2} \rfloor \in I$ gives $|\mathcal{A}| = (q - p + o(1))\binom{n}{\lfloor n/2 \rfloor}$. Our next result shows that this is asymptotically best possible.

Theorem 3. *Let $p, q \in \mathbb{N}$ be coprime with $p < q$. Let $\mathcal{A}$ be a set system on ground set $[n]$ such that $p|A \setminus B| \neq q|B \setminus A|$ for all distinct $A, B \in \mathcal{A}$. Then $|\mathcal{A}| \leq (q - p + o(1))\binom{n}{\lfloor n/2 \rfloor}$.*

The following lemma performs an analogous role to that of Lemma 2 in the proof of Theorem 1.

Lemma 4. *Let $\mathcal{A}$ be a set system on $[n]$ such that $p|A \setminus B| \neq q|B \setminus A|$ for all distinct $A, B \in \mathcal{A}$. Then*

$$\sum_{j\in J_k} \frac{|\mathcal{A}_j|}{\binom{n}{j}} \leq 1$$

where $J_k = \{l : \lceil \frac{pn}{p+q} \rceil \leq l \leq \lfloor \frac{qn}{p+q} \rfloor, l \equiv k (\text{mod } (q - p))\}$ for $0 \leq k \leq q - p - 1$.

Proof. We only sketch the proof, as it is very similar to the proof of Lemma 2. For convenience we assume $n = (p + q)m$ (this assumption is easily removed). Fix $k \in [0, q - p - 1]$ and let $k' \equiv k - pm (\text{mod } (q - p))$ where $k' \in [0, q - p - 1]$. Pick a random ordering of $[n]$ which we denote by $(a_1, a_2, \ldots, a_{qm}, b_1, \ldots, b_{pm})$. Given this ordering let $C_i = \{a_j : j \in [qi + k']\} \cup \{b_j : j \in [pi + 1, pm]\}$ and let $\mathcal{C} = \{C_i : i \in [0, m - 1]\}$. (Here if $k' = 0$ we additionally adjoin C_m to $\mathcal{C}$.) By choice of k', we have $|C_i| \in J_k$ for all $i \in [0, m - 1]$.

Again for any C_i and C_j with $i < j$ we have $q|C_i \setminus C_j| = p|C_j \setminus C_i|$, which implies that $\mathcal{A}$ contains at most one element of $\mathcal{C}$. Using this the rest of the proof is as in Lemma 2. $\square$

The proof of Theorem 3 is now identical to the proof of Theorem 1 taking Lemma 4 in place of Lemma 2.

For simplicity we have given in Lemma 4 only the inequalities that we needed in order to prove Theorem 3. Further inequalities involving smaller level sets analogous to those in Lemma 2 can also be obtained in a similar fashion. While we have not done so here, we note that it is possible to use these inequalities to again find an exact extremal family for any given ratio $p : q$ as in Theorem 1, provided $q - p$ and n have the opposite parity and n is sufficiently large.

3. Forbidding a fixed distance

In this final section we consider how large a family $\mathcal{A}$ can be if for all $A, B \in \mathcal{A}$ we do not allow A to have a constant distance from the bottom of the subcube formed with B. For 'distance exactly 1' this would mean that we exclude $|A \setminus B| = 1$ for $A, B \in \mathcal{A}$. Here the following family $\mathcal{A}^*$ provides a lower bound: let $\mathcal{A}^*$ consist of all sets A of size $\lfloor n/2 \rfloor$ such that $\sum_{i\in A} i \equiv r (\text{mod } n)$, where $r \in \{0, \ldots, n - 1\}$ is chosen to maximise $|\mathcal{A}^*|$. Such a choice of r gives $|\mathcal{A}^*| \geq \frac{1}{n}\binom{n}{\lfloor n/2 \rfloor}$. Note that if we had $|A \setminus B| = 1$ for some $A, B \in \mathcal{A}^*$ then, since $|A| = |B|$, we would also have $|B \setminus A| = 1$. Letting $A \setminus B = \{i\}$ and $B \setminus A = \{j\}$ we then have $i - j \equiv 0 (\text{mod } n)$, giving $i = j$, a contradiction.

We suspect that this bound is best.

Conjecture 5. *Let $\mathcal{A} \subset \mathcal{P}[n]$ be a family which satisfies $|A \setminus B| \neq 1$ for all $A, B \in \mathcal{A}$. Then $|\mathcal{A}| \leq (1 + o(1))\frac{1}{n}\binom{n}{\lfloor n/2 \rfloor}$.*

The following gives an upper bound that is a factor $n^{1/2}$ larger than this.

Theorem 6. *Let $\mathcal{A} \subset \mathcal{P}[n]$ be a family such that $|A \setminus B| \neq 1$ for all $A, B \in \mathcal{A}$. Then there exists a constant C independent of n such that $|\mathcal{A}| \leq \frac{C}{n}2^n$.*

Proof. An easy estimate gives that the number of subsets of $\mathcal{A}$ in $[n]^{(\leq n/3)} \bigcup [n]^{(\geq 2n/3)}$ is at most $4\binom{n}{n/3} = o(\frac{2^n}{n})$. Therefore it suffices to show that $|\mathcal{A}_i| \leq \frac{C}{n}\binom{n}{i}$ for all $i \in [\frac{n}{3}, \frac{2n}{3}]$.

To see this, note that since $|A \setminus A'| \neq 1$ for all $A, A' \in \mathcal{A}$, each $B \in [n]^{(i+1)}$ contains at most one $A \in \mathcal{A}_i$. Double counting, we have

$$\frac{n}{3}|\mathcal{A}_i| \leq (n-i)|\mathcal{A}_i| = |\{(A, B) : A \in \mathcal{A}_i, B \in [n]^{(i+1)}, A \subset B\}| \leq \binom{n}{i+1} \leq 3\binom{n}{i}$$

as required. □

Our final result gives an upper bound on the size of a family $\mathcal{A}$ in which we forbid 'distance at most 1' instead of 'distance exactly 1', i.e. where we have $|A \setminus B| > 1$ for all $A, B \in \mathcal{A}$. Again, the family $\mathcal{A}^*$ constructed above gives a lower bound for this problem. In general, if we forbid 'distance at most k' then it is easily seen that the following family $\mathcal{A}_k^*$ gives a lower bound of $\frac{1}{n^k}\binom{n}{\lfloor n/2 \rfloor}$: supposing n is prime, let $\mathcal{A}_k^*$ consist of all sets A of $\lfloor n/2 \rfloor$ which satisfy $\sum_{i \in A} i^d \equiv 0 (\text{mod } n)$ for all $1 \leq d \leq k$.

Our last result provides a upper bound which matches this up to a multiplicative constant. The proof is again a Katona-type argument. Here the condition $|A \setminus B| > k$ rather than $|A \setminus B| \neq k$ seems to be crucial.

Theorem 7. *Let $k \in \mathbb{N}$. Suppose $\mathcal{A}$ is a set system on $[n]$ such that $|A \setminus B| > k$ for all distinct $A, B \in \mathcal{A}$. Then $|\mathcal{A}| \leq \frac{(2^k - o(1))}{n^k}\binom{n}{\lfloor n/2 \rfloor}$.*

Proof. Consider the family $\partial^{(k)}\mathcal{A}$, the k-shadow of $\mathcal{A}$, where

$$\partial^{(k)}\mathcal{A} = \{B \in \mathcal{P}[n] : B = A \setminus C \text{ for some } A \in \mathcal{A} \text{ and } C \subset A \text{ with } |C| = k\}.$$

Since $\mathcal{A}$ does not contain A, B with $|A \setminus B| \leq k$, every element of $\partial^{(k)}\mathcal{A}$ is contained in at most one element of $\mathcal{A}$. Therefore we have

$$|\partial^{(k)}\mathcal{A}| = \sum_{i=0}^{n} (i)_k |\mathcal{A}_i| \tag{4}$$

where $i_k = i\,(i-1)\cdots(i-k+1)$. Now, since $\mathcal{A}$ does not contain A, B with $|A \setminus B| \leq k$, it follows that $\partial^{(k)}\mathcal{A}$ is an antichain, and so by Sperner's theorem we have

$$|\partial^{(k)}\mathcal{A}| \leq \binom{n}{\lfloor n/2 \rfloor}. \tag{5}$$

Finally, an estimate of the sum of binomial coefficients (Appendix A of [1]) gives

$$\sum_{i=0}^{\frac{n}{2}-n^{2/3}} |\mathcal{A}_i| \leq \sum_{i=0}^{\frac{n}{2}-n^{2/3}} \binom{n}{i} \leq e^{-n^{1/3}}2^n. \tag{6}$$

Combining (4)–(6) we obtain

$$\begin{aligned}
\binom{n}{\lfloor n/2 \rfloor} &\geq \sum_{i=0}^{\frac{n}{2}-n^{2/3}} (i)_k|\mathcal{A}_i| + \sum_{i=\frac{n}{2}-n^{2/3}}^{n} (i)_k|\mathcal{A}_i| \\
&\geq \sum_{i=0}^{\frac{n}{2}-n^{2/3}} \left(\frac{n}{2} - n^{2/3}\right)_k |\mathcal{A}_i| - \left(\frac{n}{2} - n^{2/3}\right)_k e^{-n^{1/3}}2^n + \sum_{i=\frac{n}{2}-n^{2/3}}^{n} \left(\frac{n}{2} - n^{2/3}\right)_k |\mathcal{A}_i| \\
&= \left(\frac{n}{2} - o(n)\right)^k |\mathcal{A}| - o\left(\binom{n}{\lfloor n/2 \rfloor}\right)
\end{aligned}$$

which gives the desired result. □

Taking $k = 1$ in Theorem 7 we obtain an upper bound which differs by a factor of 2 from the lower bound given by the family $\mathcal{A}^*$. It would be interesting to close this gap.

Acknowledgment

Research of the second author is supported by a Benefactor Scholarship from St. John's College, Cambridge.

References

[1] N. Alon, J. Spencer, The Probabilistic Method, third ed., Wiley, 2008.
[2] B. Bollobás, Combinatorics: Set Systems, Hypergraphs, Families of Vectors and Combinatorial Probability, first ed., Cambridge University Press, 1986.
[3] G. Kalai, Personal communication, 2010.
[4] G.O.H. Katona, Two applications of Sperner type theorems, Period. Math. Hungar. 3 (1973) 19–26.
[5] E. Sperner, Ein Satz über Untermengen einer endlichen Menge, Math. Z. 27 (1928) 544–548.