A Tverberg Type Theorem for Matroids

Imre Bárány Gil Kalai Roy Meshulam

November 29, 2016

Abstract

Let $b(M)$ denote the maximal number of disjoint bases in a matroid M. It is shown that if M is a matroid of rank $d+1$, then for any continuous map f from the matroidal complex M into $\mathbb{R}^d$ there exist $t \geq \sqrt{b(M)}/4$ disjoint independent sets $\sigma_1, \ldots, \sigma_t \in M$ such that $\bigcap_{i=1}^t f(\sigma_i) \neq \emptyset$.

1 Introduction

Tverberg's theorem [15] asserts that if $V \subset \mathbb{R}^d$ satisfies $|V| \geq (k-1)(d+1)+1$, then there exists a partition $V = V_1 \cup \cdots \cup V_k$ such that $\bigcap_{i=1}^k \mathrm{conv}(V_i) \neq \emptyset$. Tverberg's theorem and some of its extensions may be viewed in the following general context. For a simplicial complex X and $d \geq 1$, let the *affine Tverberg number* $T(X,d)$ be the maximal t such that for any affine map $f : X \to \mathbb{R}^d$, there exist disjoint simplices $\sigma_1, \ldots, \sigma_t \in X$ such that $\bigcap_{i=1}^t f(\sigma_i) \neq \emptyset$. The *topological Tverberg number* $TT(X,d)$ is defined similarly where now $f : X \to \mathbb{R}^d$ can be an arbitrary continuous map.

Let Δ_n denote the n-simplex and let $\Delta_n^{(d)}$ be its d-skeleton. Using the above terminology, Tverberg's theorem is equivalent to $T(\Delta_{(k-1)(d+1)}, d) = k$ which is clearly the same as $T(\Delta_{(k-1)(d+1)}^{(d)}, d) = k$. Similarly, the topological Tverberg theorem of Bárány, Shlosman and Szűcs [2] states that if p is prime then $TT(\Delta_{(p-1)(d+1)}, d) = p$. Schöneborn and Ziegler [14] proved that this implies the stronger statement $TT(\Delta_{(p-1)(d+1)}^{(d)}, d) = p$. This result was extended by Özaydin [13] for the case when p is a prime power. The question whether the topological Tverberg theorem holds for every p that is not a prime power had been open for long. Very recently, and quite surprisingly, Frick [7] has constructed a counterexample for every non-prime power p. His construction is built on work by Mabillard and Wagner [10]. See also [4] and [1] for further counterexamples.

There is a colourful version of Tverberg theorem. To state it let $n = r(d+1)-1$ and assume that the vertex set V of Δ_n is partitioned into $d+1$ classes (called colours) and that each colour class contains exactly r vertices. We define $Y_{r,d}$ as the subcomplex of Δ_n (or $\Delta_n^{(d)}$) consisting of those $\sigma \subset V$ that contain at most one vertex from each colour class. The colourful Tverberg theorem of Živaljević and Vrećica [16] asserts that $TT(Y_{2p-1,d}, d) \geq p$ for prime p which implies that $TT(Y_{4k-1,d}, d) \geq k$ for arbitrary k. A neat and more recent theorem of Blagojević, Matschke, and Ziegler [5] says that $TT(Y_{r,d}, d) = r$ if $r+1$ is a prime, which is clearly best possible. Further information on Tverberg's theorem can be found in Matoušek's excellent book [12].

Let M be a matroid (possibly with loops) with rank function ρ on the set V. We identify M with the simplicial complex on V whose simplices are the independent sets of M. It is well known (see e.g. Theorem 7.8.1 in [3]) that M is $(\rho(V)-2)$-connected. Note that both $\Delta_n^{(d)}$ and $Y_{r,d}$ are matroids of rank $d+1$. In this note we are interested in bounding $TT(M,d)$ for a general matroidal complex M. Let $b(M)$ denote the maximal number of pairwise disjoint bases in M. Our main result is the following

Theorem 1. *Let M be a matroid of rank $d+1$. Then*

$$TT(M,d) \geq \sqrt{b(M)}/4 \quad .$$

In Section 2 we give a lower bound on the topological connectivity of the deleted join of matroids. In Section 3 we use this bound and the approach of [2, 16] to prove Theorem 1.

2 Connectivity of Deleted Joins of Matroids

We recall some definitions. For a simplicial complex Y on a set V and an element $v \in V$ such that $\{v\} \in Y$, denote the *star* and *link* of v in Y by

$$\begin{aligned} \mathrm{st}(Y,v) &= \{\sigma \subset V : \{v\} \cup \sigma \in Y\} \\ \mathrm{lk}(Y,v) &= \{\sigma \in \mathrm{st}(Y,v) : v \notin \sigma\}. \end{aligned}$$

For a subset $V' \subset V$ let $Y[V'] = \{\sigma \subset V' : \sigma \in Y\}$ be the induced complex on V'. We regard $\mathrm{st}(Y,v)$, $\mathrm{lk}(Y,v)$ and $Y[V']$ as complexes on the original set V (keeping in mind that not all elements of V have to be vertices of these complexes). Let $f_i(Y)$ denote the number of i-simplices in Y. Let $X_1,\ldots,X_k$ be simplicial complexes on the same set V and let $V_1,\ldots,V_k$ be k disjoint copies of V with bijections $\pi_i : V \to V_i$. The *join* $X_1 * \cdots * X_k$ is the simplicial complex on $\bigcup_{i=1}^k V_i$ with simplices $\bigcup_{i=1}^k \pi_i(\sigma_i)$ where $\sigma_i \in X_i$. The *deleted join* $(X_1 * \cdots * X_k)_\Delta$ is the subcomplex of the join consisting of all simplices $\bigcup_{i=1}^k \pi_i(\sigma_i)$ such that $\sigma_i \cap \sigma_j = \emptyset$ for $1 \leq i \neq j \leq k$. When all X_i are equal to X, we denote their deleted join by X_Δ^{*k}. Note that $\mathbb{Z}_k$ acts freely on X_Δ^{*k} by cyclic shifts.

Claim 2. *Let $M_1,\ldots,M_k$ be matroids on the same set V, with rank functions $\rho_1,\ldots,\rho_k$. Suppose $A_1,\ldots,A_k$ are disjoint subsets of V such that A_i is a union of at most m independent sets in M_i. Then $Y=(M_1 * \cdots * M_k)_\Delta$ is $(\lceil \frac{1}{m+1}\sum_{i=1}^k |A_i| \rceil - 2)$-connected.*

Proof: Let $c = \lceil \frac{1}{m+1}\sum_{i=1}^k |A_i| \rceil - 2$. If $k=1$ then $\rho_1(V) \geq \left\lceil \frac{|A_1|}{m} \right\rceil$ and hence $Y = M_1$ is $(\left\lceil \frac{|A_1|}{m} \right\rceil - 2)$-connected. For $k \geq 2$ we establish the Claim by induction on $f_0(Y) = \sum_{i=1}^k f_0(M_i)$. If $f_0(Y)=0$ then all A_i's are empty and the Claim holds. We henceforth assume that $f_0(Y) > 0$ and consider two cases:
a) If $M_i = M_i[A_i]$ for all $1 \leq i \leq k$ then $Y = M_1 * \cdots * M_k$ is a matroid of rank

$$\sum_{i=1}^k \rho_i(V) \geq \sum_{i=1}^k \left\lceil \frac{|A_i|}{m} \right\rceil \geq \left\lceil \frac{\sum_{i=1}^k |A_i|}{m} \right\rceil .$$

Hence Y is $(\left\lceil \frac{\sum_{i=1}^k |A_i|}{m} \right\rceil - 2)$-connected.
b) Otherwise there exists an $1 \leq i_0 \leq k$ such that $M_{i_0} \neq M_{i_0}[A_{i_0}]$. Choose an element

$v \in V - A_{i_0}$ such that $\{v\} \in M_{i_0}$. Without loss of generality we may assume that $i_0 = 1$ and that $v \notin \bigcup_{i=1}^{k-1} A_i$. Let $S = \bigcup_{i=1}^{k} V_i$ and let $Y_1 = Y[S - \{\pi_1(v)\}]$, $Y_2 = \mathrm{st}(Y, \pi_1(v))$. Then

$$Y_1 = (M_1[V - \{v\}] * M_2 * \cdots * M_k)_\Delta.$$

Noting that $f_0(Y_1) = f_0(Y) - 1$ and applying the induction hypothesis to the matroids $M_1[V - \{v\}], M_2, \ldots, M_k$ and the sets $A_1, \ldots, A_k$, it follows that Y_1 is c-connected. We next consider the connectivity of $Y_1 \cap Y_2$. Write $A_1 = \bigcup_{j=1}^{t} C_j$ where $t \leq m$, $C_j \in M_1$ for all $1 \leq j \leq t$, and the C_j's are pairwise disjoint. Since $\{v\} \in M_1$, it follows that there exist $\{C'_j\}_{j=1}^{t}$ such that $C'_j \subset C_j$, $|C'_j| \geq |C_j| - 1$, and $C'_j \in \mathrm{lk}(M_1, v)$ for all $1 \leq j \leq t$. Let

$$M'_i = \begin{cases} \mathrm{lk}(M_1, v) & i = 1, \\ M_i[V - \{v\}] & 2 \leq i \leq k, \end{cases}$$

and

$$A'_i = \begin{cases} \bigcup_{j=1}^{t} C'_j & i = 1, \\ A_i & 2 \leq i \leq k-1, \\ A_k - \{v\} & i = k. \end{cases}$$

Observe that

$$Y_1 \cap Y_2 = \mathrm{lk}(Y, \pi_1(v)) = (M'_1 * \cdots * M'_k)_\Delta$$

and that A'_i is a union of at most m independent sets in M'_i for all $1 \leq i \leq k$. Noting that $f_0(Y_1 \cap Y_2) \leq f_0(Y) - 1$ and applying the induction hypothesis to the matroids $M'_1, \ldots, M'_k$ and the sets $A'_1, \ldots, A'_k$, it follows that $Y_1 \cap Y_2$ is c'-connected where

$$\begin{aligned} c' &= \left\lceil \frac{1}{m+1} \sum_{i=1}^{k} |A'_i| \right\rceil - 2 \\ &= \left\lceil \frac{1}{m+1} \left(\sum_{j=1}^{t} |C'_j| + \sum_{i=2}^{k-1} |A_i| + |A_k - \{v\}| \right) \right\rceil - 2 \\ &\geq \left\lceil \frac{1}{m+1} \left(|A_1| - m + \sum_{i=2}^{k-1} |A_i| + |A_k| - 1 \right) \right\rceil - 2 = c - 1. \end{aligned}$$

As Y_1 is c-connected, Y_2 is contractible and $Y_1 \cap Y_2$ is $(c-1)$-connected, it follows that $Y = Y_1 \cup Y_2$ is c-connected.

□

Let M be a matroid on V with $b(M) = b$ disjoint bases $B_1, \ldots, B_b$. Let $I_1 \cup \cdots \cup I_k$ be a partition of $[b]$ into almost equal parts $\lfloor \frac{b}{k} \rfloor \leq |I_i| \leq \lceil \frac{b}{k} \rceil$. Applying Claim 2 with $M_1 = \cdots = M_k = M$ and $A_i = \cup_{j \in I_i} B_j$, we obtain:

Corollary 3. *The connectivity of M_Δ^{*k} is at least*

$$\frac{b\rho(V)}{\lceil \frac{b}{k} \rceil + 1} - 2 \quad .$$

We suggest the following:

Conjecture 4. *For any $k \geq 1$ there exists an $f(k)$ such that if $b(M) \geq f(k)$ then M_Δ^{*k} is $(k\rho(V)-2)$-connected.*

Remark: Let M be the rank 1 matroid on m points $M = \Delta_{m-1}^{(0)}$. The chessboard complex $C(k,m)$ is the k-fold deleted join M_Δ^{*k}. Chessboard complexes play a key role in the works of Živaljević and Vrećica [16] and Blagojević, Matschke, and Ziegler [5] on the colourful Tverberg theorem. Let $k \geq 2$. Garst [9] and Živaljević and Vrećica [16] proved that $C(k, 2k-1)$ is $(k-2)$-connected. On the other hand, Friedman and Hanlon [8] showed that $\tilde{H}_{k-2}(C(k,2k-2);\mathbb{Q}) \neq 0$, so $C(k,2k-2)$ is not $(k-2)$-connected. This implies that the function $f(k)$ in Conjecture 4 must satisfy $f(k) \geq 2k-1$.

3 A Tverberg Type Theorem for Matroids

We recall some well-known topological facts (see [2]). For $m \geq 1, k \geq 2$ we identify the sphere $S^{m(k-1)-1}$ with the space

$$\left\{ (y_1,\ldots,y_k) \in (\mathbb{R}^m)^k : \sum_{i=1}^k |y_i|^2 = 1 \ , \ \sum_{i=1}^k y_i = 0 \in \mathbb{R}^m \right\} \ .$$

The cyclic shift on this space defines a $\mathbb{Z}_k$ action on $S^{m(k-1)-1}$. The action is free for prime k.

The *k-fold deleted product* of a space X is the $\mathbb{Z}_k$-space given by

$$X_D^k = X^k - \{(x,\ldots,x) \in X^k : x \in X\} \ .$$

For $m \geq 1$ define a $\mathbb{Z}_k$-map

$$\phi_{m,k} : (\mathbb{R}^m)_D^k \to S^{m(k-1)-1}$$

by

$$\phi_{m,k}(x_1,\ldots,x_k) = \frac{(x_1 - \frac{1}{k}\sum_{i=1}^k x_i, \ldots, x_k - \frac{1}{k}\sum_{i=1}^k x_i)}{(\sum_{j=1}^k |x_j - \frac{1}{k}\sum_{i=1}^k x_i|^2)^{1/2}} \ .$$

We'll also need the following result of Dold [6] (see also Theorem 6.2.6 in [11]):

Theorem 5 (Dold)**.** *Let p be a prime and suppose X and Y are free $\mathbb{Z}_p$-spaces such that $\dim Y = k$ and X is k-connected. Then there does not exist a $\mathbb{Z}_p$-map from X to Y.*

Proof of Theorem 1: Let M be a matroid on the vertex set V, and let $f: M \to \mathbb{R}^d$ be a continuous map. Let $b = b(M)$ and choose a prime $\sqrt{b}/4 \leq p \leq \sqrt{b}/2$. We'll show that there exist disjoint simplices (i.e. independent sets) $\sigma_1,\ldots,\sigma_p \in M$ such that $\bigcap_{i=1}^p f(\sigma_i) \neq \emptyset$. Suppose for contradiction that $\bigcap_{i=1}^p f(\sigma_i) = \emptyset$ for all such choices of σ_i's. Then f induces a continuous $\mathbb{Z}_p$-map

$$f_* : M_\Delta^{*p} \to (\mathbb{R}^{d+1})_D^p$$

as follows. If $x_1,\ldots,x_p$ have pairwise disjoint supports in M and $(t_1,\ldots,t_p) \in \mathbb{R}_+^p$ satisfies $\sum_{i=1}^p t_i = 1$ then

$$f_*(t_1\pi_1(x_1) + \cdots + t_p\pi_p(x_p)) = (t_1, t_1 f(x_1), \ldots, t_p, t_p f(x_p)) \in (\mathbb{R}^{d+1})_D^p \ .$$

Hence $\phi_{d+1,p} f_*$ is a $\mathbb{Z}_p$-map between the free $\mathbb{Z}_p$-spaces M_Δ^{*p} and $S^{(d+1)(p-1)-1}$. This however contradicts Dold's Theorem since by Corollary 3 the connectivity of M_Δ^{*p} is at least

$$\frac{b(d+1)}{\lceil \frac{b}{p} \rceil + 1} - 2 \geq (d+1)(p-1) - 1$$

by the choice of p.

□

Acknowledgements. Research of Imre Bárány was partially supported by ERC advanced grant 267165, and by Hungarian National grant K 83767. Research of Gil Kalai was supported by ERC advanced grant 320924. Research of Roy Meshulam is supported by ISF and GIF grants.

References

[1] S. Avvakumov, I. Mabillard, A. Skopenkov, U. Wagner, Eliminating higher-multiplicity intersections, III. Codimension 2, (2015) 16 pages, arXiv:1511.03501

[2] I. Bárány, S. Shlosman and A. Szűcs, On a topological generalization of a theorem of Tverberg, *J. London Math. Soc.* **23**(1981) 158–164.

[3] A. Björner, Topological methods. in *Handbook of Combinatorics* (R. Graham, M. Grötschel, and L. Lovász, Eds.), 1819–1872, North-Holland, Amsterdam, 1995.

[4] P. V. M. Blagojević, F. Frick and G. M. Ziegler, Barycenters of polytope Skeleta and counterexamples to the topological Tverberg conjecture, via constraints, (2015) 6 pages, arXiv:1508.02349

[5] P. V. M. Blagojević, B. Matschke, G. M. Ziegler, Optimal bounds for the colored Tverberg problem, *J. European Math. Soc.* **17** (2015) 739–754.

[6] A. Dold, Simple proofs of some Borsuk-Ulam results, *Contemp. Math.* **19**(1983) 65-69.

[7] F. Frick, Counterexamples to the topological Tverberg conjecture, (2015), 3 pages arXiv:1502.00947

[8] J. Friedman and P. Hanlon, On the Betti numbers of chessboard complexes, *J. Algebraic Combin.* **8** (1998) 193-203.

[9] P. Garst, Cohen-Macaulay complexes and group actions, Ph.D.Thesis, The University of Wisconsin - Madison, 1979.

[10] I. Mabillard and U. Wagner, Eliminating higher-multiplicity intersections, I. A Whitney trick for Tverberg-type problems, (2015), 46 pages, arXiv:1508.02349

[11] J. Matoušek, *Using the Borsuk-Ulam theorem*, Springer-Verlag, Berlin, 2003.

[12] J. Matoušek, *Lectures on discrete geometry*, Springer-Verlag, New York, 2002.

[13] M.Özaydin, Equivariant maps for the symmetric group, 1987. Available at http://minds.wisconsin.edu/handle/1793/63829

[14] T. Schöneborn and G. M. Ziegler, The topological Tverberg theorem and winding numbers, *J. Combin. Theory Ser. A* **112**(2005) 82-104.

[15] H. Tverberg, A generalization of Radon's theorem. *J. London Math. Soc.* **41** (1966), 123128.

[16] R. Živaljević, S. Vrećica, The colored Tverberg's problem and complexes of injective functions, *J. Combin. Theory Ser. A* **61**(1992) 309–318.

Authors' addresses:

Imre Bárány
Rényi Institute, Hungarian Academy of Sciences
POB 127, 1364 Budapest, Hungary
and
Department of Mathematics, University College London
Gower Street, London, WC1E 6BT, UK
E-mail: barany@renyi.hu

Gil Kalai
Einstein Institute of Mathematics, Hebrew University
Jerusalem 9190, Israel
E-mail: kalai@math.huji.ac.il

Roy Meshulam
Department of Mathematics, Technion
Haifa 32000, Israel
E-mail: meshulam@math.technion.ac.il