

Proper Coloring of Geometric Hypergraphs*

Balázs Keszegh[†]

Dömötör Pálvölgyi[‡]

Abstract

We study whether for a given planar family \mathcal{F} there is an m such that any finite set of points can be 3-colored such that any member of \mathcal{F} that contains at least m points contains two points with different colors. We conjecture that if \mathcal{F} is a family of pseudo-disks, then $m = 3$ is sufficient. We prove that when \mathcal{F} is the family of all homothetic copies of a given convex polygon, then such an m exists. We also study the problem in higher dimensions.

1 Introduction

In the present paper, we primarily focus on the following proper coloring problem. Given a finite set of points in the plane, S , we want to color the points of S with a small number of colors such that every member of some given geometric family \mathcal{F} that intersects S in many points will contain at least two different colors.

Pach conjectured in 1980 [27] that for every convex set D there is an m such that any finite set of points admits a 2-coloring such that any translate of D that contains at least m points contains both colors. This conjecture inspired a series of papers studying the problem and its variants - for a recent survey, see [30]. Eventually, the conjecture was shown to hold in the case if D is a convex polygon in a series of papers [28, 40, 36], but disproved in general [29]. In fact, the conjecture fails for any D with a smooth boundary, e.g., for a disk.

It follows from basic properties of generalized Delaunay-triangulations (to be defined later) that for any convex D it is possible to 4-color any finite set of points such that any *homothetic copy*¹ of D that contains at least two points will contain at least two colors. Therefore, the only case left open is when we have 3 colors. We conjecture that for 3 colors the following holds.

*First author is supported by the Hungarian National Research, Development and Innovation Office – NKFIH under the grant K 116769. Second author is supported by the Marie Skłodowska-Curie action of the EU, under grant IF 660400.

[†]Alfréd Rényi Institute of Mathematics, Hungarian Academy of Sciences, Budapest, Hungary.

[‡]Department of Pure Mathematics and Mathematical Statistics, University of Cambridge, UK.

¹A homothetic copy or homothet of a set is a scaled and translated copy of it (rotations are *not* allowed).

Conjecture 1. *For every plane convex set D there is an m such that any finite set of points admits a 3-coloring such that any homothetic copy of D that contains at least m points contains two points with different colors.*

The special case of Conjecture 1 when D is a disk has been posed earlier in [15], and is also still open. Our main result is the proof of Conjecture 1 for convex polygons.

Theorem 2. *For every convex n -gon D there is an m such that any finite set of points admits a 3-coloring such that any homothetic copy of D that contains at least m points contains two points with different colors.*

The constant m which we get from our proof depends not only on the number of sides, but also on the shape of the polygon. However, we conjecture that this dependence can be removed, and in fact the following stronger conjecture holds for any *pseudo-disk arrangement*. We define a pseudo-disk arrangement as a family of planar bodies whose boundaries are Jordan curves such that any member of the family intersects the boundary of any other member in a connected curve.²

Conjecture 3. *For any pseudo-disk arrangement any finite set of points admits a 3-coloring such that any pseudo-disk that contains at least 3 points contains two points with different colors.*

This conjecture also has a natural dual counterpart.

Conjecture 4. *The members of any pseudo-disk arrangement admit a 3-coloring such that any point that is contained in at least 3 pseudo-disks is contained in two pseudo-disks with different colors.*

We believe that these are fundamental problems about geometric hypergraphs, and find it quite surprising that they have not been studied much.

The rest of this paper is organized as follows. In the rest of this section, we give an overview of related results. In Section 2 we give the definition and basic properties of generalized Delaunay triangulations. In Section 4 we prove Theorem 2, using the proof method of [1]. In Section 5 we study the higher dimensional variants of the problem and present some constructions. In Section 6 we briefly discuss further related topics.

Previous results.

Most earlier papers on colorings and geometric ranges focused not on proper colorings, but on *polychromatic colorings* and its dual, *cover-decomposition*. In the polychromatic k -coloring problem our goal is to color the points of some finite S with k colors such that every member of some family \mathcal{F} that contains many points of S contains *all* k colors.

²This is slightly non-standard, as usually it is assumed that any two boundaries intersect at most twice (the structure of the boundary curves is also called a *pseudo-circle arrangement*). We use our definition as in our case any family of homothets of a convex set forms a pseudo-disk arrangement, see, e.g., [25].

Gibson and Varadarajan [12] have shown that for every convex polygon D there is a c_D such that every finite set of points can be k -colored such that any translate of D that contains at least $m_k = c_D k$ points contains all k colors. Whether such a polychromatic k -coloring exists for homothetic copies of convex polygons for any m_k is an open problem, which would be a significant strengthening of our Theorem 2. This conjecture has only been proved in a series of papers for triangles [6, 7, 17, 18, 19, 21] and very recently [1] for squares³ using the Four Color Theorem. The derived upper bound on m_k is polynomial in k in both cases. It is, however, conjectured in a much more general setting [34] that whenever m_k exists, it is linear in k , just like for the translates of convex polygons. This is also known for *axis-parallel bottomless rectangles*:⁴ any finite set of points can be k -colored such that any axis-parallel bottomless rectangle that contains at least $m_k = 3k - 2$ points contains all k colors [3]. (The value of m_k is known to be optimal only for $k = 2$ [15].) Their proof reduces the problem to coloring a one-dimensional *dynamic point set* with respect to intervals, which turns the problem into a variant of online colorings. We will not introduce these notions here; for some related results, see [7, 16, 21].

The dual notion of polychromatic colorings is *cover-decomposition*. In the cover-decomposition problem we are given some finite family \mathcal{F} that covers some region m_k -fold (i.e., each point of the region is contained in at least m_k members of \mathcal{F}) and our goal is to partition \mathcal{F} into k families that each cover the region. By considering the respective underlying incidence hypergraphs in the polychromatic coloring and in the cover-decomposition problems, one can see that they are about colorings of dual hypergraphs.⁵ In fact, the two problems are equivalent for translates of a given set, as the following observation shows.

Observation 5 (Pach [27]). *For any set D , if \mathcal{H} is the inclusion hypergraph of some points and some translates of D , then the dual hypergraph of \mathcal{H} is also such an inclusion hypergraph.*

Combining this with the result of Gibson and Varadarajan [12], we get that for every convex polygon D there is a c_D such that if \mathcal{F} is an $(m_k = c_D k)$ -fold covering of a region by the translates of D , then \mathcal{F} can be decomposed into k coverings of the same region. It follows from the proofs about polychromatic k -colorings for triangles that the same holds for coverings by the homothets of a triangle, with a polynomial bound on m_k (this function is slightly weaker than what is known for the polychromatic k -coloring problem). By homothets of other convex polygons, however, surprisingly for any m it is possible to construct an indecomposable m -fold covering [24]. The homothets of the square are the only family which is known to behave differently for polychromatic coloring and cover-decomposition.

Proper colorings of (primal and dual) geometric hypergraphs have been first studied systematically in [15], for halfplanes and axis-parallel bottomless rectangles, proving several

³And since affine transformation have no effect on the question, also for parallelograms.

⁴A bottomless rectangle is a planar set of the form $\{(x, y) \mid a \leq x \leq b, y \leq c\}$.

⁵The dual of a hypergraph $\mathcal{H} = (V, \mathcal{E})$ is the hypergraph $\overline{\mathcal{H}}$ with vertex set \mathcal{E} , edge set V , and with the incidences reversed, i.e., in $\overline{\mathcal{H}}$ a vertex corresponding to $e \in \mathcal{E}$ is contained in the edge corresponding to $v \in V$ if and only if v is contained in e in \mathcal{H} .

lower and upper bounds. Other papers mainly studied the dual variant of our question. Smorodinsky [38] has shown that any pseudo-disk family can be colored with a bounded number of colors such that every point covered at least twice is covered by at least two differently colored disks. He also proved that 4 colors are sufficient for disks, and later this was generalized by Cardinal and Korman [8] to the homothetic copies of any convex body. Smorodinsky has also shown that any family of n axis-parallel rectangles can be colored with $O(\log n)$ colors such that every region covered at least twice is covered by at least two differently colored rectangles. This was shown to be optimal by Pach and Tardos [31]; they proved that there is a C such that for every m there is a family of n axis-parallel rectangles such that for any $(C \frac{\log n}{m \log m})$ -coloring of the family there is a point covered by exactly m rectangles, all of the same color. It was shown by Chen et al. [9], answering a question of Brass, Moser and Pach [5], that for every c and m there is a finite point set S such that for every c -coloring of S there is an axis-parallel rectangle containing m points that are all of the same color. This latter construction is the closest to the problem that we study. It also shows why the pseudo-disk property is crucial in Conjecture 3.

Rotation invariant families have also been studied. It was shown in [32] using the Hales-Jewett theorem [14] that for every c and m there is a finite planar point set S such that for every c -coloring of S there is a line containing m points that are all of the same color. Using duality, they have also shown that this implies that for every c and m there is a finite collection of lines such that for every c -coloring of the lines there is a point covered by exactly m lines, all of the same color. Halfplanes, on the other hand, behave much more like one-dimensional sets and admit polychromatic colorings. It was shown in [39], improving on earlier results [2, 15, 33], that any finite point set can be k -colored such that any halfplane that contains $m_k = 2k - 1$ points contains all k colors, and this is best possible. In the dual, they have shown that any finite set of halfplanes can be k -colored such that any point that is covered by at least $m_k = 3k - 2$ halfplanes is covered by all k colors. This bound is not known to be best possible, except for $k = 2$ [11]. Except for this last sharpness bound, all other results were extended to pseudo-halfplanes in [20].

2 Generalized Delaunay triangulations

With a slight perturbation of the points, it is enough to prove Theorem 2 (or any similar statement) for the case when the points are in a *general position with respect to* the convex polygon D in the sense that no two points are on a line parallel to a side of D and no four points are on the boundary of a homothet of D . In the following, we always suppose that our point set S is in general position with respect to D . We will also suppose that D is open - this does not alter the validity of the statements and makes some of the arguments simpler to present.

We say that a halfplane H is *supporting* D at a side ab of D if H contains D and ab is on the boundary of H . A point $s \in S$ is *extremal* (for a side ab) if a translate of a halfplane supporting D at a side ab contains s but no other point of S .

We define a plane graph whose vertices are the points of S , called the *generalized*

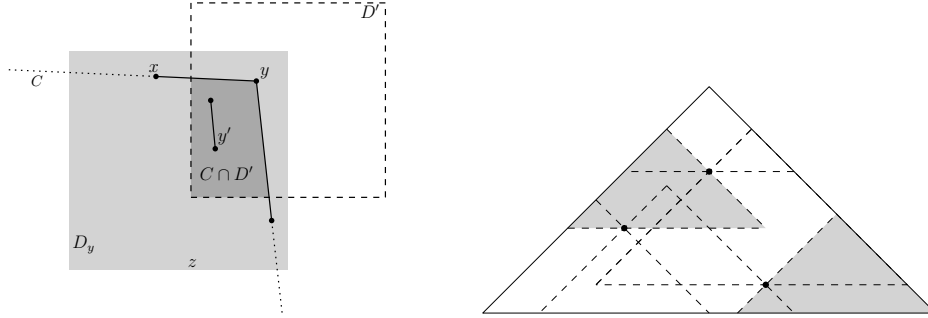


Figure 1: Illustration for Proposition 8 on the left and for Theorem 10 for triangles to the right (shading is only to improve visibility.)

Delaunay triangulation of S with respect to D , and we denote it by $\mathcal{DT}_D(S)$, or when clear from the context, simply by \mathcal{DT} . As it leads to no confusion, we will not differentiate between the points and their associated vertices. Two points of S are connected by a straight-line edge in \mathcal{DT} if there is a homothet of D that contains only them from S . It follows [4, 22] that \mathcal{DT} is a well-defined connected plane graph whose inner faces are triangles. We recall a few simple statements about \mathcal{DT} , most of which also appeared in [1].

Proposition 6. *If D' is a homothet of D , the points $D' \cap S$ induce a connected graph of $\mathcal{DT}_D(S)$.*

Corollary 7 ([1]). *If D' is a homothet of D and e is an edge of \mathcal{DT} that splits D' into two parts, then one of these parts does not contain any points from S .*

We continue with a proposition that is quite similar to a statement of [1].

Proposition 8. *Suppose that D' and D_y are two homothets of D , $x, y, y', z \in D_y \cap S$ and $y, y' \in D'$ but $x, z \notin D'$, x and z are neighbors of y in \mathcal{DT} , and for one of the two cones whose sides are the halflines starting from y as yx and yz , denoted by C , we have $C \cap D' \subset D_y$ and $y' \in C \cap D'$. (See Figure 1 for an illustration.) Then y' has a neighbor in \mathcal{DT} that is contained in $D' \cap D_y$.*

Proof. Using Proposition 6, y' has a neighbor in D' . Since \mathcal{DT} is planar, this neighbor must be in $C \cap D' \subset D' \cap D_y$. \square

3 Framework

In this section we outline the main idea behind the proof of Theorem 2. As discussed in Section 2, we can suppose that S is in general position with respect to D , and we can consider the generalized Delaunay triangulation $\mathcal{DT} = \mathcal{DT}_D(S)$. We will take an initial coloring of S that has some nice properties. More specifically, we need a 3-coloring for

which the assumptions of the following lemma hold for $c = 3$ and for some constant t that only depends on D .

Lemma 9. *For every convex polygon D for every c and t there is an m such that if for a c -coloring of a point set S and a set of points $R \subset S$ it holds that*

- (i) *for every homothet D' if $D' \cap S$ is monochromatic with at least t vertices, D' contains a point of R ,*
- (ii) *for every homothet D' if D' contains t points from R colored with the same color, D' also contains a point from $S \setminus R$ that has the same color,*

then there is a c -coloring of S such that no homothet that contains at least m points of S is monochromatic.

To prove Lemma 9, we use the following theorem about the so-called *self-coverability* of convex polygons.

Theorem 10 ([18]). *Given a closed convex polygon D and a collection of k points in its interior, we can take $c_D k$ homothets of D whose union is D such that none of the homothets contains any of the given points in its interior, where c_D is a constant that depends only on D .*

Proof of Lemma 9. The proper c -coloring will be simply taking the c -coloring given in the hypothesis, and recoloring each vertex in R arbitrarily to a different color. Now we prove the correctness of this new coloring.

If a homothet D' contains $m \geq ct$ points from R , then it contains at least t points from R that originally had the same color. Using (ii), it will have a point both in R and in $S \setminus R$ that had the same color. These points will have different colors after the recoloring, thus D' will not be monochromatic.

If a homothet D' contains less than ct points from R , let us apply Theorem 10 with $R' = D' \cap R$. This gives $c_D ct$ homothets (where c_D comes from Theorem 10), each of which might contain at most three points on their boundaries (which include the points from R'), thus by the pigeonhole principle at least one homothet, D'' , contains no points from R and at least $\frac{m-3c_D ct}{c_D ct}$ points from $S \setminus R$. If we set $m = c_D ct(t+3)$, this is at least t . Thus, by (i), D'' was not monochromatic before the recoloring. As the recoloring does not affect points in $S \setminus R$, after the recoloring D'' (and thus also D') still contains two points that have different colors. \square

Therefore, to prove Theorem 2, we only need to show that we can find a coloring with three colors that satisfy the conditions of Lemma 9 for some t .

4 Proof of Theorem 2

In this section we prove Theorem 2, that is, we show that for every convex polygon D there is an m such that any finite set of points S admits a 3-coloring such that there is no monochromatic homothet of D that contains at least m points. If one could find a 3-coloring where every monochromatic component is bounded, then that would immediately prove Theorem 2. This, however, is not true in general [23], only for bounded degree graphs [10], but the \mathcal{DT} can have arbitrarily high degree vertices for any convex polygon, thus we cannot apply this result. Instead, we use the following result (whose proof is just a couple of pages).

Theorem 11 (Poh [37]; Goddard [13]). *The vertices of any planar graph can be 3-colored such that every monochromatic component is a path.*

To prove Theorem 2, apply Theorem 11 to \mathcal{DT} to obtain a 3-coloring where every monochromatic component is a path. As discussed in Section 3, it is sufficient to show that for $t = 4n + 12$ (where n denotes the number of sides of D) there is a set of points $R \subset S$ for which

- (i) for every homothet D' if $D' \cap S$ is monochromatic with at least t vertices, D' contains a point of R ,
- (ii) for every homothet D' if D' contains t points from R colored with the same color, D' also contains a point from $S \setminus R$ that has the same color.

Now we describe how to select R . First, partition every monochromatic path that has at least t vertices into subpaths, called *sections*, such that the number of vertices of each section is at least $\frac{t}{4}$ but at most $\frac{t}{2}$. We call such a section *cutable* if there is a monochromatic homothet of D that contains all of its points. R will consist of exactly one point from each cutable section. These points are selected arbitrarily from the non-extremal points of each section, except that they are required to be non-adjacent on their monochromatic path. By ruling out the extremal points and the two end vertices of a section, by the pigeonhole principle we can select such a point from each section if $\frac{t}{4} \geq n + 3$. For an $r \in R$ we denote its section by σ_r and a (fixed) monochromatic homothet containing it by D_r .

Now we prove that R satisfies the requirements (i) and (ii). If a homothet D' is monochromatic with at least t vertices, it must contain at least t consecutive vertices of a monochromatic path, and thus also a section. Because of D' this section is cutable, and thus contains a point of R .

To prove (ii), suppose that a homothet D' contains t points from R colored with the same color, red. Denote these points by R' . It is sufficient to prove that for some $r \in R'$ another point from σ_r is also contained in D' . Suppose the contrary. As the neighbors of a point in R are not in R but red, they must be outside D' , or (ii) holds. For each $r \in R'$, denote the geometric embedding of the two edges adjacent to r in σ_r by Λ_r . Therefore, Λ_r will intersect the boundary of D' in two points for each $r \in R'$. We claim that these points are usually on the same side of D' .

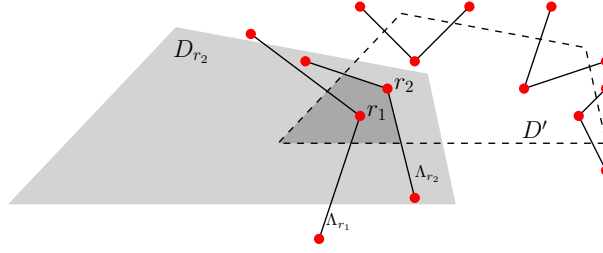


Figure 2: Proof of Proposition 12.

Proposition 12. *Both intersection points of Λ_r and D' are on the same side for all but at most n points of $r \in R'$.*

Proof. Suppose that there are more than n points $r \in R'$ for which Λ_r intersects D' in two sides. For each such point $r \in R'$, for (at least) one of the two cones whose sides are the halflines starting in Λ_r , denoted by C_r , we have $C_r \cap D' \subset D_r$. Since the intersection $C_r \cap D'$ is a connected curve, it contains a vertex of D' . Using the pigeonhole principle, there are two points, $r_1, r_2 \in R'$, such that C_{r_1} and C_{r_2} contain the same vertex of D' . (See Figure 2.) In this case r_1 and r_2 would be in the configuration described in Proposition 8, one playing the role of y , the other of y' . The neighbor of y' in $D' \cap D_y$ given by Proposition 8 must also be red, as it is contained in D_y . As the red neighbors of any red point of R are not in R , we have found a red point from $S \setminus R$ in D' , proving (ii). \square

Divide the points $r \in R'$ for which Λ_r intersects only one side of D' into n groups, R'_1, \dots, R'_n , depending on which side is intersected. By the pigeonhole principle there is a group, R'_i , that contains at least $\frac{t-n}{n} \geq 3$ points. Suppose without loss of generality that the side ab intersected by Λ_r for $r \in R'_i$ is horizontal, bounding D' from below. For each $r \in R'_i$, fix and denote by x_r a point from σ_r that is above the line ab . (Such a point exists because no $r \in R$ is extremal in σ_r .) Denote the path from r to x_r in σ_r by P_r , and the neighbor of r in P_r by q_r .

The geometric embedding of P_r starts above ab with r , then goes below ab as $q_r \notin D'$, and finally x_r is again above the line uv . Denote the first intersection (starting from r) of the embedding of the path P_r with the line ab by $\alpha_r = r\bar{q}_r \cap \bar{a}\bar{b}$, and the next intersection by β_r . Since $|R'_i| \geq 3$, without loss of generality, there are $r_1, r_2 \in R'_i$ such that β_{r_1} is to the left of α_{r_1} and β_{r_2} is to the left of α_{r_2} . For readability and simplicity, let $x_i = x_{r_i}$, $P_i = P_{r_i}$, $q_i = q_{r_i}$, $\alpha_i = \alpha_{r_i}$, $\beta_i = \beta_{r_i}$.

Without loss of generality suppose that α_1 is to the left of α_2 . Recall that P_2 contains only red points, of which only r_2 is in R . Therefore, no other vertex of P_2 can be in D' . If β_2 is to the right of α_1 , then one of the edges of P_2 would separate r_1 and r_2 in the sense described in Corollary 7. (See Figure 3.) As this cannot happen, β_2 is to the left of α_1 .

This implies that $q_1 \notin P_2$ is in the convex hull of P_2 below the ab line. Take the point $q \in S \setminus P_2$ with the smallest y -coordinate such that q is in the convex hull of P_2 below the ab line. As q is not an extremal point of S , it is connected in \mathcal{DT} to some point in S whose y -coordinate is smaller. By the definition of q , this neighbor must be in P_2 . As

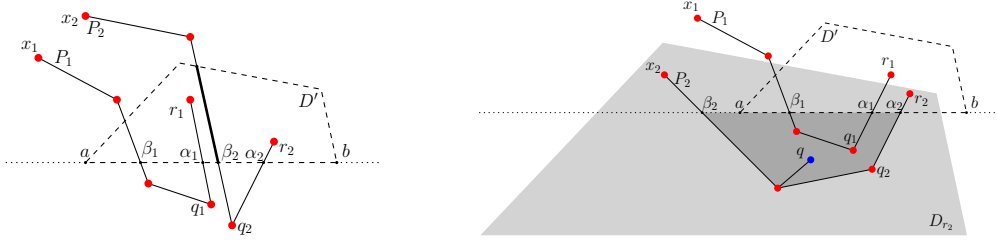


Figure 3: The two cases at the end of the proof of Theorem 2. To the left, β_2 is to the right of α_1 , the part of the edge splitting D' is bold. To the right, β_2 is to the left of α_1 , the shaded regions must contain q_1 .

the end vertices of P_2 , r_2 and x_2 , are above the ab line, q is connected to an inner vertex of a monochromatic red path. Since every monochromatic component is a path, q cannot be red. The homothet D_{r_2} contains the red vertices of P_2 and thus all the points in the convex hull of P_2 . But D_{r_2} is monochromatic, so it cannot contain the non-red point q , a contradiction.

This finishes the proof of Theorem 2.

5 Higher dimensions

In this section we study the following natural extension of the problem to higher dimensions. Given a finite set of points $S \in \mathbb{R}^d$ and a family \mathcal{F} , can we c -color S such that every $F \in \mathcal{F}$ contains at least two colors? First we show that while for $d = 3$ there might be hope to find such colorings for natural families, but not in higher dimensions. Define a (positive) *hextant* in \mathbb{R}^4 as the set of points $\{(x, y, z, w) \mid x \geq x_0, y \geq y_0, z \geq z_0, w \geq w_0\}$ for some real numbers x_0, y_0, z_0, w_0 .

Theorem 13. *For any c and m there is a finite point set S such that for every c -coloring of S there is a hextant that contains exactly m points of S , all of the same color.*

Proof. As mentioned in the introduction, Pach and Tardos [31] have shown that for any c and m there is a finite planar point set S such that for every c -coloring of S there is an axis-parallel rectangle that contains exactly m points of S , all of the same color. Place this construction on the $\Pi = \{(x, y, z, w) \mid x + y = 0, z + w = 0\}$ subplane of \mathbb{R}^4 . A hextant $\{(x, y, z, w) \mid x \geq x_0, y \geq y_0, z \geq z_0, w \geq w_0\}$ intersects Π in $\{(x, y, z, w) \mid x_0 \leq x = -y \leq -y_0, z_0 \leq z = -w \leq -w_0\}$, which is a rectangle whose sides are parallel to the lines $\{x + y = 0, z = w = 0\}$ and $\{x = y = 0, z + w = 0\}$, respectively. Taking these perpendicular lines as axis, thus any “axis-parallel” rectangle of Π is realizable by an appropriate hextant, and the theorem follows. \square

For $d = 3$, however, the following might hold.

Conjecture 14. *For every convex set $D \subset \mathbb{R}^3$ there is an m such that any finite set of points admits a 4-coloring such that any homothetic copy of D that contains at least m points contains at least two colors.*

If we put some sufficiently high number of colors instead of 4 in Conjecture 14, then the statement we get is true already for $m = 2$ for the family of balls, as there is a vertex of bounded degree in the graph of any 3-dimensional *Delaunay-tessellation* [26], and thus its chromatic number is bounded. The same most likely applies to homothets of other convex sets (and in more general, any 3-dimensional *pseudo-ball arrangement*, which we do not define here), but we are not aware of any papers dealing with generalized Delaunay-tessellations - it is hard to imagine that the same arguments would not work, but we do not want to go into definitions and technical details about this problem.

The reason why Conjecture 14 is stated with 4 colors is the following construction.

Theorem 15. *For every m there is a finite set of points $S \in \mathbb{R}^3$ such that for any 3-coloring of S there is a unit ball that contains exactly m points of S , all of the same color.*

Earlier such a construction with unit balls was only known for 2-colorings [32]. For 2-colorings the analogue of Theorem 15 was also shown to hold when the family is the translates of any polyhedron instead of unit balls [35]. The only known positive result is that for *octants* any finite set of points can be 2-colored such that any octant that contains at least 9 points contains both colors [17, 21]. We do not, however, know the answer for 3-colorings and the translates or homothets of polyhedra.

The rest of this section contains a sketch of the proof of Theorem 15. The reason why we only sketch the proof is that it is a simple modification of the planar construction with similar properties for unit disks from [29].

Abstract hypergraph.

First we define the abstract hypergraph that will be realized with unit balls. It is a straight-forward generalization of the hypergraph defined first in [35]. Instead of a single parameter, m , the induction will be on three parameters, k, ℓ and m . For any k, ℓ, m we define the (multi)hypergraph $\mathcal{H}(k, \ell, m) = (V(k, \ell, m), \mathcal{E}(k, \ell, m))$ recursively. The edge set $\mathcal{E}(k, \ell, m)$ will be the disjoint union of three sets, $\mathcal{E}(k, \ell, m) = \mathcal{E}_1(k, \ell, m) \cup \mathcal{E}_2(k, \ell, m) \cup \mathcal{E}_3(k, \ell, m)$. All edges belonging to $\mathcal{E}_1(k, \ell, m)$ will be of size k , all edges belonging to $\mathcal{E}_2(k, \ell, m)$ will be of size ℓ , and all edges belonging to $\mathcal{E}_3(k, \ell, m)$ will be of size m . We will prove that in every 3-coloring of $\mathcal{H}(k, \ell, m)$ with colors c_1, c_2 and c_3 there will be an edge in $\mathcal{E}_i(k, \ell, m)$ such that all of its vertices are colored c_i for some $i \in \{1, 2, 3\}$. If $k = \ell = m$, we get an m -uniform hypergraph that cannot be properly 3-colored.

Now we give the recursive definition. Define $\mathcal{H}(1, 1, 1)$ as a hypergraph on one vertex with three edges containing it, with one edge in each of $\mathcal{E}_1(1, 1, 1)$, $\mathcal{E}_2(1, 1, 1)$ and $\mathcal{E}_3(1, 1, 1)$. If at least one of k, ℓ, m is bigger than 1, define $\mathcal{H}(k, \ell, m)$ recursively from $\mathcal{H}(k-1, \ell, m)$,

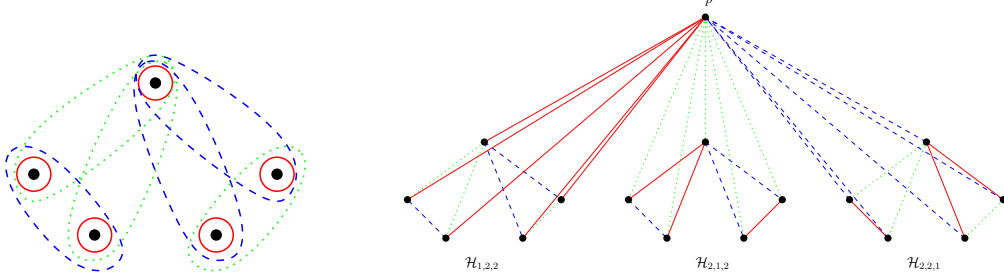


Figure 4: $\mathcal{H}(1, 2, 2)$ drawn with sets (left) and $\mathcal{H}(2, 2, 2)$ drawn as graph (right). Different colors represent the edges from the different families \mathcal{E}_i .

$\mathcal{H}(k, \ell - 1, m)$, $\mathcal{H}(k, \ell, m - 1)$ by adding a “new” vertex p as follows.

$$V(k, \ell, m) = V(k - 1, \ell, m) \cup V(k, \ell - 1, m) \cup V(k, \ell, m - 1) \cup \{p\}.$$

If $k = 1$, then $\mathcal{E}_1(1, \ell, m) = \{\{v\} : v \in V(1, \ell, m)\}$, otherwise

$$\mathcal{E}_1(k, \ell, m) = \{e \cup \{p\} : e \in \mathcal{E}_1(k - 1, \ell, m)\} \cup \mathcal{E}_1(k, \ell - 1, m) \cup \mathcal{E}_1(k, \ell, m - 1).$$

Similary, if $\ell = 1$, then $\mathcal{E}_2(k, 1, m) = \{\{v\} : v \in V(k, 1, m)\}$, otherwise

$$\mathcal{E}_2(k, \ell, m) = \{e \cup \{p\} : e \in \mathcal{E}_2(k, \ell - 1, m)\} \cup \mathcal{E}_2(k - 1, \ell, m) \cup \mathcal{E}_2(k, \ell, m - 1),$$

and if $m = 1$, then $\mathcal{E}_3(k, \ell, 1) = \{\{v\} : v \in V(k, \ell, 1)\}$, otherwise

$$\mathcal{E}_3(k, \ell, m) = \{e \cup \{p\} : e \in \mathcal{E}_3(k, \ell, m - 1)\} \cup \mathcal{E}_3(k - 1, \ell, m) \cup \mathcal{E}_3(k, \ell - 1, m).$$

Lemma 16. *In every 3-coloring of $\mathcal{H}(k, \ell, m)$ with colors c_1, c_2 and c_3 there is an edge in $\mathcal{E}_i(k, \ell, m)$ such that all of its vertices are colored c_i for some $i \in \{1, 2, 3\}$. Therefore, $\mathcal{H}(k, \ell, m)$ has no proper 3-coloring.*

The proof is a simple modification of the respective statement from [35].

Proof. If $k = \ell = m = 1$, the statement holds. Otherwise, suppose without loss of generality that the color of p is c_1 . If $k = 1$, we are done as $\{p\} \in \mathcal{E}_1(1, \ell, m)$. Otherwise, consider the copy of $\mathcal{H}(k - 1, \ell, m)$ contained in $\mathcal{H}(k, \ell, m)$. If it contains an edge in $\mathcal{E}_2(k - 1, \ell, m)$ or $\mathcal{E}_3(k - 1, \ell, m)$ such that its vertices are all colored c_2 or all colored c_3 , respectively, we are done. Otherwise, it contains an $e \in \mathcal{E}_1(k - 1, \ell, m)$ such that its vertices are all colored c_1 . But then all the vertices of $(e \cup \{p\}) \in \mathcal{E}_1(k, \ell, m)$ are also all colored c_1 , we are done. \square

Geometric realization.

Now we sketch how to realize $\mathcal{H}(k, \ell, m)$ by unit balls in \mathbb{R}^3 . The construction will build on the construction of [29], where the edges belonging to $\mathcal{E}_1(k, \ell, 1) \cup \mathcal{E}_2(k, \ell, 1)$ of $\mathcal{H}(k, \ell, 1)$ were realized by unit disks.

The vertices $V(k, \ell, m)$ will be embedded as a point set, $S(k, \ell, m)$, and the edge set $\mathcal{E}_i(k, \ell, m)$ as a collection of unit balls, $\mathcal{B}_i(k, \ell, m)$, where a point is contained in a ball if

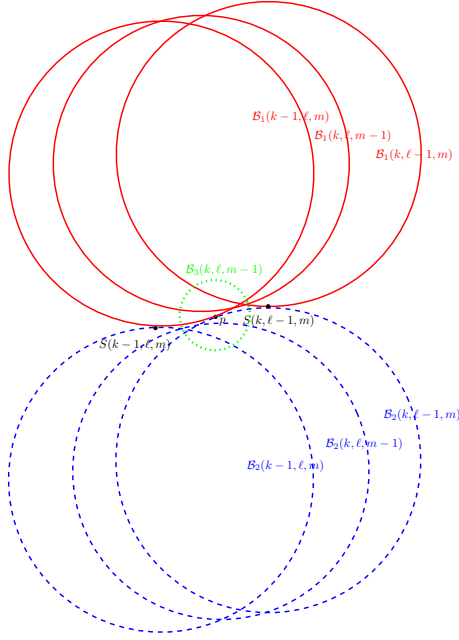


Figure 5: The intersection of $\mathcal{H}(k, \ell, m)$ with the $z = 0$ plane. Point sets/collections of balls that are at distance $O(\epsilon^5)$ are represented by a single point/ball. As the balls $\mathcal{B}_3(k-1, \ell, m)$ intersect in a $O(\epsilon^5)$ vicinity of $S(k-1, \ell, m)$ and the balls $\mathcal{B}_3(k, \ell-1, m)$ intersect in a $O(\epsilon^5)$ vicinity of $S(k, \ell-1, m)$, they are not drawn to avoid overcrowding the picture.

and only if the respective vertex is in the respective edge. All the points of $S(k, \ell, m)$ will be placed in a small neighborhood of the origin. The centers of the balls from $\mathcal{B}_1(k, \ell, m)$, $\mathcal{B}_2(k, \ell, m)$ and $\mathcal{B}_3(k, \ell, m)$ will be close to $(0, -1, 0)$, $(0, 1, 0)$ and $(0, 0, -1)$, respectively. The realization of $\mathcal{H}(1, 1, 1)$ contains only one point, the origin, and one ball in each family, centered appropriately close to the required center.

Suppose that not all of k, ℓ, m are 1, and we have already realized the hypergraphs $\mathcal{H}(k-1, \ell, m)$, $\mathcal{H}(k, \ell-1, m)$ and $\mathcal{H}(k, \ell, m-1)$. Place the new point p in the origin, and shift the corresponding realizations (i.e., the point sets, $S(k-1, \ell, m)$, $S(k, \ell-1, m)$ and $S(k, \ell, m-1)$, and the collection of balls, $\mathcal{B}(k-1, \ell, m)$, $\mathcal{B}(k, \ell-1, m)$ and $\mathcal{B}(k, \ell, m-1)$) with the following vectors, where $\epsilon = \epsilon(k, \ell, m)$ is a small enough number, but such that $\epsilon(k-1, \ell, m)$, $\epsilon(k, \ell-1, m)$ and $\epsilon(k, \ell, m-1)$ are all $O(\epsilon^5(k, \ell, m))$.

1. Shift $\mathcal{H}(k-1, \ell, m)$ with $(2\epsilon - 1.5\epsilon^3, 2\epsilon^2, 0)$.
2. Shift $\mathcal{H}(k, \ell-1, m)$ with $(-2\epsilon + 1.5\epsilon^3, -2\epsilon^2, 0)$.
3. Shift $\mathcal{H}(k, \ell, m-1)$ with $(0, 0, 2\epsilon^2)$.

For an illustration, see Figure 5.

Proposition 17. *The above construction realizes $\mathcal{H}(k, \ell, m)$.*

The proof of this proposition is a routine calculation, we only show some parts.

Proof. Denote by o_B the center of the ball B and denote by $dist(p, q)$ the Euclidean distance of two points p, q .

1. $p \in B \in \mathcal{B}_1(k-1, \ell, m)$:

$$dist(p, o_B) = (2\epsilon - 1.5\epsilon^3)^2 + (1 - 2\epsilon^2)^2 + O(\epsilon^5) = 1 - 2\epsilon^4 + O(\epsilon^5) < 1.$$

2. $p \notin B \in \mathcal{B}_1(k, \ell-1, m)$:

$$dist(p, o_B) = (2\epsilon - 1.5\epsilon^3)^2 + (1 + 2\epsilon^2)^2 + O(\epsilon^5) = 1 + 4\epsilon^2 + O(\epsilon^3) > 1.$$

3. $p \notin B \in \mathcal{B}_1(k, \ell, m-1)$:

$$dist(p, o_B) = 1^2 + (2\epsilon^2)^2 + O(\epsilon^5) = 1 + 4\epsilon^4 + O(\epsilon^5) > 1.$$

4. If $s \in S(k, \ell-1, m)$, then $s \notin B \in \mathcal{B}_1(k-1, \ell, m)$:

$$dist(s, o_B) = (4\epsilon - 3\epsilon^3)^2 + (1 - 4\epsilon^2)^2 + O(\epsilon^5) = 1 + 8\epsilon^2 + O(\epsilon^3) > 1.$$

5. If $s \in S(k, \ell-1, m)$, then $s \notin B \in \mathcal{B}_1(k, \ell, m-1)$:

$$dist(s, o_B) = (2\epsilon - 1.5\epsilon^3)^2 + (1 - 2\epsilon^2)^2 + (2\epsilon^2)^2 + O(\epsilon^5) = 1 + 2\epsilon^4 + O(\epsilon^5) > 1.$$

6. If $s \in S(k, \ell-1, m)$, then $s \notin B \in \mathcal{B}_3(k, \ell, m-1)$:

$$dist(s, o_B) = (2\epsilon - 1.5\epsilon^3)^2 + (2\epsilon^2)^2 + (1 - 2\epsilon^2)^2 + O(\epsilon^5) = 1 + 2\epsilon^4 + O(\epsilon^5) > 1.$$

7. If $s \in S(k, \ell, m-1)$, then $s \notin B \in \mathcal{B}_1(k-1, \ell, m)$:

$$dist(s, o_B) = (2\epsilon - 1.5\epsilon^3)^2 + (1 - 2\epsilon^2)^2 + (2\epsilon^2)^2 + O(\epsilon^5) = 1 + 4\epsilon^2 + O(\epsilon^3) > 1.$$

The other incidences can be checked similarly and thus Proposition 17 follows. \square

Lemma 16 and Proposition 17 imply Theorem 15 by selecting $k = \ell = m$, therefore this also finishes the proof of Theorem 15.

6 Further remarks

Combining Theorems 2 and 10, for any convex polygon, D , and for any finite point set, S , we can first find a 3-coloring of S using Theorem 2 such that every large (in the sense that it contains many points of S) homothet of D contains two differently colored points, then using Theorem 10 we can conclude that every very large homothet of D contains many points from at least two color classes, and finally we can recolor every color class separately using Theorem 2. This proves that for every k there is a 3^k -coloring such that every large homothet of D contains at least 2^k colors. Of course, the colors that we use when recoloring need not be different for each color class, so we can also prove for example that there is a 6-coloring such that every large homothet of D contains at least 3 colors. What are the best bounds of this type that can be obtained?

Given a planar graph, G , and a pair of paths on three vertices, uvw and $u'v'w'$, we say that the paths *cross* if $v = v'$ and u, u', w, w' appear in this order around v - equivalently, the two paths do not form a pseudo-disk family. A possible equivalent reformulation of Conjecture 3 is the following. Is it true that for any planar graph and any pairwise non-crossing collection of its paths, \mathcal{P} , there is a 3-coloring of the vertices such that every path from \mathcal{P} is non-monochromatic?

Finally, we would like to draw attention to the study of *realizable hypergraphs*. Unfortunately, *planar hypergraphs* are traditionally defined dully as a hypergraph whose (bipartite) incidence graph is planar. Instead, it would be more natural to define them as the hypergraphs realizable by a pseudo-disk arrangement in the sense that the vertices are embedded as points and the edges as pseudo-disks such that a point is contained in a pseudo-disk if and only if the respective vertex is in the respective edge. This would also allow one to define hypergraphs realizable in higher dimensions by a pseudo-ball arrangement. Apparently, these natural geometric hypergraphs have not yet been previously defined or studied explicitly - it is not even known whether the complete 3-uniform hypergraph on 5 vertices is realizable by pseudo-disks or not.⁶ We believe that these hypergraphs deserve more attention.

References

- [1] Eyal Ackerman, Balázs Keszegh, and Máté Vizer. Coloring points with respect to squares. In Sándor P. Fekete and Anna Lubiw, editors, *32nd International Symposium on Computational Geometry, SoCG 2016, June 14-18, 2016, Boston, MA, USA*, volume 51 of *LIPIcs*, pages 5:1–5:16. Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, 2016.

⁶See <http://mathoverflow.net/questions/255684>.

- [2] Greg Aloupis, Jean Cardinal, Sébastien Collette, Stefan Langerman, and Shakhar Smorodinsky. Coloring geometric range spaces. *Discrete & Computational Geometry*, 41(2):348–362, 2009.
- [3] Andrei Asinowski, Jean Cardinal, Nathann Cohen, Sébastien Collette, Thomas Hackl, Michael Hoffmann, Kolja Knauer, Stefan Langerman, Michał Lasoń, Piotr Micek, Günter Rote, and Torsten Ueckerdt. *Coloring Hypergraphs Induced by Dynamic Point Sets and Bottomless Rectangles*, pages 73–84. Springer Berlin Heidelberg, Berlin, Heidelberg, 2013.
- [4] Prosenjit Bose, Paz Carmi, Sébastien Collette, and Michiel H. M. Smid. On the stretch factor of convex delaunay graphs. *JoCG*, 1(1):41–56, 2010.
- [5] Peter Brass, William O. J. Moser, and János Pach. *Research problems in discrete geometry*. Springer, 2005.
- [6] Jean Cardinal, Kolja Knauer, Piotr Micek, and Torsten Ueckerdt. Making triangles colorful. *Journal of Computational Geometry*, 4:240–246, 2013.
- [7] Jean Cardinal, Kolja Knauer, Piotr Micek, and Torsten Ueckerdt. Making octants colorful and related covering decomposition problems. *SIAM journal on discrete mathematics*, 28(4):1948–1959, 2014.
- [8] Jean Cardinal and Matias Korman. Coloring planar homothets and three-dimensional hypergraphs. *Computational geometry*, 46(9):1027–1035, 2013.
- [9] Xiaomin Chen, János Pach, Mario Szegedy, and Gábor Tardos. Delaunay graphs of point sets in the plane with respect to axis-parallel rectangles. *Random Struct. Algorithms*, 34(1):11–23, 2009.
- [10] Louis Esperet and Gwenaél Joret. Colouring planar graphs with three colours and no large monochromatic components. *Combinatorics, Probability & Computing*, 23(4):551–570, 2014.
- [11] Radoslav Fulek. Coloring geometric hypergraph defined by an arrangement of half-planes. In *Proceedings of the 22nd Annual Canadian Conference on Computational Geometry, Winnipeg, Manitoba, Canada, August 9-11, 2010*, pages 71–74, 2010.
- [12] Matt Gibson and Kasturi R. Varadarajan. Decomposing coverings and the planar sensor cover problem. In *50th Annual IEEE Symposium on Foundations of Computer Science, FOCS 2009, October 25-27, 2009, Atlanta, Georgia, USA*, pages 159–168. IEEE Computer Society, 2009.
- [13] Wayne Goddard. Acyclic colorings of planar graphs. *Discrete Math.*, 91(1):91–94, 1991.

- [14] A. W. Hales and R. I. Jewett. Regularity and positional games. *Trans. Amer. Math. Soc.*, 106:222–229, 1963.
- [15] Balázs Keszegh. Coloring half-planes and bottomless rectangles. *Computational Geometry*, 45(9):495–507, 2012.
- [16] Balázs Keszegh, Nathan Lemons, and Dömötör Pálvölgyi. Online and quasi-online colorings of wedges and intervals. *Order*, 33(3):389–409, 2016.
- [17] Balázs Keszegh and Dömötör Pálvölgyi. Octants are cover-decomposable. *Discrete & Computational Geometry*, 47(3):598–609, 2012.
- [18] Balázs Keszegh and Dömötör Pálvölgyi. Convex polygons are self-coverable. *Discrete & Computational Geometry*, 51(4):885–895, 2014.
- [19] Balázs Keszegh and Dömötör Pálvölgyi. Octants are cover-decomposable into many coverings. *Computational Geometry*, 47(5):585–588, 2014.
- [20] Balázs Keszegh and Dömötör Pálvölgyi. An abstract approach to polychromatic coloring: Shallow hitting sets in aba-free hypergraphs and pseudohalfplanes. In Ernst W. Mayr, editor, *Graph-Theoretic Concepts in Computer Science - 41st International Workshop, WG 2015, Garching, Germany, June 17-19, 2015, Revised Papers*, volume 9224 of *Lecture Notes in Computer Science*, pages 266–280. Springer, 2015.
- [21] Balázs Keszegh and Dömötör Pálvölgyi. More on decomposing coverings by octants. *Journal of Computational Geometry*, 6(1):300–315, 2015.
- [22] Rolf Klein. *Concrete and abstract Voronoi diagrams*, volume 400. Springer Science & Business Media, 1989.
- [23] Jon M. Kleinberg, Rajeev Motwani, Prabhakar Raghavan, and Suresh Venkatasubramanian. Storage management for evolving databases. In *38th Annual Symposium on Foundations of Computer Science, FOCS '97, Miami Beach, Florida, USA, October 19-22, 1997*, pages 353–362. IEEE Computer Society, 1997.
- [24] István Kovács. Indecomposable coverings with homothetic polygons. *Discrete & Computational Geometry*, 53(4):817–824, 2015.
- [25] L. Ma. *Bisectors and Voronoi Diagrams for Convex Distance Functions*. PhD thesis, FernUniversität Hagen, Germany, 2000.
- [26] Atsuyuki Okabe, Barry N Boots, Kokichi Sugihara, and David George Kendall. *Spatial tessellations : concepts and applications of Voronoi diagrams*. Wiley series in probability and mathematical statistics. Wiley & Sons, Chichester, New York, Brisbane, 1992.

- [27] János Pach. Decomposition of multiple packing and covering. In *2. Kolloquium über Diskrete Geometrie*, pages 169–178. Institut für Mathematik der Universität Salzburg, 1980.
- [28] János Pach. Covering the plane with convex polygons. *Discrete & Computational Geometry*, 1:73–81, 1986.
- [29] János Pach and Dömötör Pálvölgyi. Unsplittable coverings in the plane. *Advances in Mathematics*, 302:433–457, 2016.
- [30] János Pach, Dömötör Pálvölgyi, and Géza Tóth. Survey on decomposition of multiple coverings. In Imre Bárány, Károly J. Böröczky, Gábor Fejes Tóth, and János Pach, editors, *Geometry — Intuitive, Discrete, and Convex*, volume 24 of *Bolyai Society Mathematical Studies*, pages 219–257. Springer Berlin Heidelberg, 2013.
- [31] János Pach and Gábor Tardos. Coloring axis-parallel rectangles. *Journal of Combinatorial Theory, Series A*, 117(6):776–782, 2010.
- [32] János Pach, Gábor Tardos, and Géza Tóth. Indecomposable coverings. *Canadian mathematical bulletin*, 52(3):451–463, 2009.
- [33] János Pach and Géza Tóth. Decomposition of multiple coverings into many parts. In *Proceedings of the twenty-third annual symposium on Computational geometry*, pages 133–137. ACM, 2007.
- [34] Dömötör Pálvölgyi. Decomposition of geometric set systems and graphs, phd thesis. *arXiv preprint arXiv:1009.4641*, 2010.
- [35] Dömötör Pálvölgyi. Indecomposable coverings with concave polygons. *Discrete & Computational Geometry*, 44(3):577–588, 2010.
- [36] Dömötör Pálvölgyi and Géza Tóth. Convex polygons are cover-decomposable. *Discrete & Computational Geometry*, 43(3):483–496, 2010.
- [37] K. S. Poh. On the linear vertex-arboricity of a planar graph. *J. Graph Theory*, 14(1):73–75, 1990.
- [38] Shakhar Smorodinsky. On the chromatic number of geometric hypergraphs. *SIAM J. Discrete Math.*, 21(3):676–687, 2007.
- [39] Shakhar Smorodinsky and Yelena Yuditsky. Polychromatic coloring for half-planes. *Journal of Combinatorial Theory, Series A*, 119(1):146 – 154, 2012.
- [40] Gábor Tardos and Géza Tóth. Multiple coverings of the plane with triangles. *Discrete & Computational Geometry*, 38(2):443–450, 2007.