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More on lines in Euclidean Ramsey theory

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Abstract. Let ℓ m be a sequence of m points on a line with consecutive points at distance one. Answering a question raised by Fox and the first author and independently by Arman and Tsaturian, we show that there is a natural number m and a red/blue-colouring of E n for every n that contains no red copy of ℓ 3 and no blue copy of ℓ m.

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1. Introduction

Let E n denote n-dimensional Euclidean space, that is, R n equipped with the Euclidean metric. Given two sets X 1, X 2 ⊂ E n, we write E n → (X 1, X 2) if every red/blue-coloring of E n contains either a red copy of X 1 or a blue copy of X 2, where a copy for us will always mean an isometric copy. Conversely, E n ↛ (X 1, X 2) means that there is some red/blue-coloring of E n which contains neither a red copy of X 1 nor a blue copy of X 2.

The study of which sets X 1, X 2 ⊂ E n satisfy the relation E n → (X 1, X 2) is a particular case of the Euclidean Ramsey problem, which has a long history going back to a series of seminal papers [6–8] of Erdős, Graham, Montgomery, Rothschild, Spencer and Straus in the 1970s. Despite the vintage of the problem, surprisingly little progress has been made since these foundational papers (though see [9, 12] for some important positive results). For instance, it is an open problem, going back to the papers of Erdős et al. [7], as to whether, for every n, there is m such that E n → (X, X) for every X ⊂ E n with |X| = m.

Write ℓ m for the set consisting of m points on a line with consecutive points at distance one. Perhaps because it is a little more accessible than the general problem, the question of determining which n and X satisfy the relation E n → (ℓ 2, X) has received considerable attention. For instance, it is known [11, 14] that E 2 → (ℓ 2, X) for every four-point set X ⊂ E 2 and that E 2 ↛ (ℓ 2, ℓ 3). On the other hand [5], there is a set X of 8 points in the plane, namely, a regular heptagon with its center, such that E 2 ↛ (ℓ 2, X).

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In higher dimensions, by combining results of Szlam [13] and Frankl and Wilson [10], it was observed by Fox and the first author [4] that $\mathbb{E}^n \twoheadrightarrow (\ell_2, \ell_m)$ provided $m \leq 2^{cn}$ for some positive constant $c$ (see also [1, 2] for some better bounds in low dimensions). Our concern here will be with a question raised independently by Fox and the first author [4] and also by Arman and Tsaturian [1], namely, as to whether an analogous result holds with $\ell_2$ replaced by $\ell_3$. That is, for every natural number $m$, is there a natural number $n$ such that $\mathbb{E}^n \twoheadrightarrow (\ell_3, \ell_m)$? We answer this question in the negative.

**Theorem 1.** There exists a natural number $m$ such that $\mathbb{E}^n \twoheadrightarrow (\ell_3, \ell_m)$ for all $n$.

Before our work, the best result that was known in this direction was a 50-year-old result of Erdős et al. [6], who showed that $\mathbb{E}^n \twoheadrightarrow (\ell_6, \ell_6)$ for all $n$. Their proof uses a spherical colouring, where all points at the same distance from the origin receive the same colour. We will also use a spherical colouring, though, unlike the colouring in [6], which is entirely explicit, our colouring will be partly random.

**2. Preliminaries**

In this short section, we note two key lemmas that will be needed in our proof. The first says that certain real-valued quadratic polynomials are reasonably well-distributed modulo a prime $q$.

**Lemma 2.** Let $p(x) = x^2 + \alpha x + \beta$, where $\alpha$ and $\beta$ are real numbers, and let $q$ be a prime number. Then, for $m = q^3$, the set $\{p(i)\}_{i=1}^m$ overlaps with at least $q/6$ of the intervals $[j, j+1)$ with $0 \leq j \leq q-1$ when considered mod $q$.

**Proof.** By a standard argument using the pigeonhole principle, there exists some $k \leq q^2$ such that $|ka| \leq 1/q$ mod $q$. We split into two cases, depending on whether $k$ is a multiple of $q$ or not.

Suppose first that $k \not\equiv 0 \bmod q$ and consider the set of values $\{p(i)\}_{i=1}^q$. Note first that $\{j^2\}_{j=1}^q$ is a set of $(q+1)/2$ distinct integers mod $q$, so, since $k$ is not a multiple of $q$, the same is also true of the set $\{k^2i^2\}_{i=1}^q$. Hence, letting $p_1(x) = x^2 + \beta$, we see that the set $\{p_1(ki)\}_{i=1}^q$ overlaps with at least $q/2$ of the intervals $[j, j+1)$ with $0 \leq j \leq q-1$ when considered mod $q$. But $|kia| \leq 1$ mod $q$ for all $1 \leq i \leq q$, so that $|p(ki) - p_1(ki)| \leq 1$ for all $1 \leq i \leq q$. Therefore, since exactly three different intervals are within distance one of any particular interval, the set $\{p(\ell)p(ki)\}_{i=1}^q$ overlaps with at least $q/6$ of the intervals $[j, j+1)$ mod $q$.

Suppose now that $k = sq$ for some $s \leq q$. Then $sq\alpha = rq + c$ for some $|c| \leq 1/q$, which implies that $\alpha = \frac{r}{s^2} + c'$, where $|c'| \leq 1/q^2$. Without loss of generality, we may assume that $r$ and $s$ have no common factors. Consider now the polynomial $p_2(x) = x^2 + \frac{r}{s^2} x$ and the set $\{p_2(\ell)|_{\ell=1}^q$. Since $p_2(s) = s^2i^2 + ri$, it is easy to check that $p_2(s\ell) \equiv p_2(s)\ell$ mod $q$ if and only if $s^2(i+j) + r \equiv 0$ mod $q$. Since $r$ and $s$ are coprime, this implies that the set $\{p_2(\ell)|_{\ell=1}^q$ takes at least $q/2$ values mod $q$. Hence, letting $p_3(x) = x^2 + \frac{r}{s^2} x + \beta$, we see that the set $\{p_3(\ell)|_{\ell=1}^q$ overlaps with at least $q/2$ of the intervals $[j, j+1)$ with $0 \leq j \leq q-1$ when considered mod $q$. But, since $|\alpha - r/s| \leq 1/q^2$, we have that $|p(s\ell) - p_3(s\ell)| = |\alpha - \frac{r}{s^2}|s \leq 1$, so that, as above, the set $\{p(\ell)p(s\ell)|_{\ell=1}^q$ overlaps with at least $q/6$ of the intervals $[j, j+1)$ mod $q$. \hfill $\square$

Given $M$ real polynomials $p_1, \ldots, p_M$ in $N$ variables, a vector $\sigma \in \{-1,0,1\}^M$ is called a sign pattern of $p_1, \ldots, p_M$ if there exists some $x \in \mathbb{R}^N$ such that the sign of $p_i(x)$ is $\sigma_i$ for all $1 \leq i \leq M$. The second result we need is the Oleinik–Petrovsky–Thom–Milnor theorem (see, for example, [3]), which, for $N$ fixed, gives a polynomial bound for the number of sign patterns.

**Lemma 3.** For $M \geq N \geq 2$, the number of sign patterns of $M$ real polynomials in $N$ variables, each of degree at most $D$, is at most $\left(50DM/N\right)^N$. 

3. Proof of Theorem 1

Suppose that $a_1, a_2, a_3 \in \mathbb{R}^n$ form a copy of $\ell_3$ with $|a_1 - a_2| = |a_2 - a_3| = 1$. If the points are at distances $x_1, x_2$ and $x_3$, respectively, from the origin $o$ and the angle $a_1a_2o = \theta$, then we have

$$x_1^2 = x_2^2 + 1 - 2x_2 \cos \theta$$

and

$$x_3^2 = x_2^2 + 1 + 2x_2 \cos \theta.$$

Adding the two gives

$$x_1^2 + x_3^2 = 2x_2^2 + 2.$$

Similarly, if $a_1, a_2, \ldots, a_m \in \mathbb{R}^n$ form a copy of $\ell_m$ with $|a_i - a_{i+1}| = 1$ for all $i = 1, 2, \ldots, m - 1$, then, again writing $x_i$ for the distance of $a_i$ from the origin, we have

$$x_{i-1}^2 + x_{i+1}^2 = 2x_i^2 + 2$$

for all $i = 2, \ldots, m - 1$. Given these observations, our aim will be to colour $\mathbb{R}_{\geq 0}$ so that there is no red solution to $y_1 + y_3 = 2y_2 + 2$ and no blue solution to the system $y_{i-1} + y_{i+1} = 2y_i + 2$ with $i = 2, \ldots, m - 1$. Assuming that we have such a colouring $\chi$, we can simply colour a point $a \in \mathbb{R}^n$ by $\chi(\lfloor |a|^2 \rfloor)$ and it is easy to check that there is no red copy of $\ell_3$ and no blue copy of $\ell_m$.

We have therefore moved our problem to one of finding a natural number $m$ and a colouring $\chi$ of $\mathbb{R}_{\geq 0}$ with no red solution to $y_1 + y_3 = 2y_2 + 2$ and no blue solution to the system $y_{i-1} + y_{i+1} = 2y_i + 2$ with $i = 2, \ldots, m - 1$. Let $q$ be a prime number. We will take $m = q^3$ and define $\chi$ by choosing an appropriate colouring $\chi'$ of $\mathbb{Z}_q$ and then setting $\chi(y) = \chi'(\lfloor y \rfloor \mod q)$ for all $y \in \mathbb{R}_{\geq 0}$. Our aim now is to show that there is a suitable choice for $\chi'$. For this, we consider a random red/blue-colouring $\chi'$ of $\mathbb{Z}_q$ and show that, for $q$ sufficiently large, the probability that $\chi$ contains either of the banned configurations is small.

Concretely, suppose that $\mathbb{Z}_q$ is coloured randomly in red and blue with each element of $\mathbb{Z}_q$ coloured red with probability $p = q^{-3/4}$ and blue with probability $1 - p$. With this choice, the expected number of solutions in red to any of the equations $y_1 + y_3 = 2y_2 + c$ with $c \in \{1, 2, 3\}$ is at most

$$3p^3q^2 + 9p^2q < 12q^{-1/4} < \frac{1}{2},$$

where we used that there are at most $3q$ solutions to any of our 3 equations with two of the variables $\{y_1, y_2, y_3\}$ being equal and that $q$ is sufficiently large. Note that if there are indeed no red solutions to these three equations over $\mathbb{Z}_q$, then there is no red solution to $y_1 + y_3 = 2y_2 + 2$ in the colouring $\chi$ of $\mathbb{R}$. Indeed, if $y_1 = n_1 + \varepsilon_1$ with $0 \leq \varepsilon_1 < 1$, then $n_1$ is coloured red in $\chi'$ and

$$n_1 + n_3 = 2n_2 + 2 + 2\varepsilon_2 - \varepsilon_1 - \varepsilon_3.$$

But $|2\varepsilon_2 - \varepsilon_1 - \varepsilon_3| < 2$, so we must have

$$n_1 + n_3 = 2n_2 + c$$

for $c \in \{1, 2, 3\}$. However, we know that there are no red solutions to any of these equations in the colouring $\chi'$, so there is no red solution to $y_1 + y_3 = 2y_2 + 2$ in the colouring $\chi$.

For the blue configurations, we first observe that if the $y_i$ satisfy the equations $y_{i-1} + y_{i+1} = 2y_i + 2$ with $i = 2, \ldots, m - 1$ with $y_1 = a$ and $y_2 = a + d$, then $y_i = a + (i-1)d + (i^2 - 3i + 2)$. In particular, by Lemma 2, at least $q/6$ elements of the sequence $y_1, \ldots, y_m$ lie in different intervals $[j, j+1)$ with $0 \leq j < q - 1$ when considered mod $q$.

Our aim now is to apply Lemma 3 to count the number of different ways in which a set of solutions $(y_1, y_2, \ldots, y_m)$ to our system of equations can overlap the collection of intervals $[j, j+1)$ mod $q$. Without loss of generality, we may assume that $0 \leq a, d < q$. Since, under this assumption, any set of solutions over $\mathbb{R}$ to our system of equations is contained in the interval $[0, 2m^2]$, it will suffice to count the number of feasible overlaps with the intervals $[j, j+1)$ with $0 \leq j < 2m^2 - 1$. 

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Since we need to check at most two linear inequalities in the two variables $a$ and $d$ to check whether each of the $m$ points are placed in each of the $2m^2$ intervals, we can apply Lemma 3 with $N = 2$, $D = 1$ and $M = 2 \cdot m \cdot 2m^2 = 4m^3$ to conclude that the points $y_1, \ldots, y_m$ overlap the intervals $[j, j+1)$ with $0 \leq j \leq 2m^2 - 1$ in at most $(100m^3)^2 = 10^4 m^6$ different ways. But now, since at least $q/6$ of the $y_i$ must always be in distinct intervals, a union bound implies that the probability we have a blue solution to our system of equations is at most

$$10^4 m^6 (1 - q^{-3/4}) q/6 < \frac{1}{2}$$

for $m$ sufficiently large. Combined with our earlier estimate for the probability of a red solution to $y_1 + y_3 = 2y_2 + 2$, we see that for $m$ sufficiently large ($m = 10^{50}$ will suffice) there exists a colouring with no red $\ell_3$ and no blue $\ell_m$, as required.

4. Concluding remarks

We say that a set $X \subset \mathbb{E}^d$ is Ramsey if for every natural number $r$ there exists $n$ such that every $r$-colouring of $\mathbb{E}^n$ contains a monochromatic copy of $X$. In [4], it was shown that a set $X$ is Ramsey if and only if for every natural number $m$ and every fixed $K \subset \mathbb{E}^m$ there exists $n$ such that $\mathbb{E}^n \rightarrow (X, K)$. We suspect that there may be an even simpler characterisation.

**Conjecture 4.** A set $X$ is Ramsey if and only if for every natural number $m$ there exists $n$ such that $\mathbb{E}^n \rightarrow (X, \ell_m)$.

Of course, by the result mentioned above, we already know that if $X$ is Ramsey, then $\mathbb{E}^n \rightarrow (X, \ell_m)$ for $n$ sufficiently large. It therefore remains to show that if $X$ is not Ramsey, then there exists $m$ such that $\mathbb{E}^n \nrightarrow (X, \ell_m)$ for all $n$. To prove this in full generality might be difficult. However, an important result of Erdős et al. [6] says that if $X$ is Ramsey, then it must be spherical, in the sense that it must be contained in the surface of a sphere of some dimension. Thus, a first step towards Conjecture 4 might be to prove the following.

**Conjecture 5.** For every non-spherical set $X$, there exists a natural number $m$ such that $\mathbb{E}^n \nrightarrow (X, \ell_m)$ for all $n$.

The simplest example of a non-spherical set is the line $\ell_3$, so our main result may be seen as a verification of Conjecture 5 in this particular case. The next case of interest seems to be when $X$ consists of three points $a_1, a_2, a_3$ on a line, but now with $|a_1 - a_2| = 1$ and $|a_2 - a_3| = \alpha$ for some irrational $\alpha$.

References


