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To cite this version:
Xavier Goaoc, Alfredo Hubard, Rémi de Joannis de Verclos, Jean-Sébastien Sereni, Jan Volec. Limits of Order Types *. 2018. hal-01913144

HAL Id: hal-01913144
https://hal.science/hal-01913144
Preprint submitted on 6 Nov 2018

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Limits of Order Types

Xavier Goaoc† Alfredo Hubard‡ Rémi de Joannis de Verclos§
Jean-Sébastien Sereni¶ Jan Volec∥

November 6, 2018

Abstract

We apply ideas from the theory of limits of dense combinatorial structures to study order types, which are combinatorial encodings of finite point sets. Using flag algebras we obtain new numerical results on the Erdős problem of finding the minimal density of 5- or 6-tuples in convex position in an arbitrary point set, and also an inequality expressing the difficulty of sampling order types uniformly. Next we establish results on the analytic representation of limits of order types by planar measures. Our main result is a rigidity theorem: we show that if sampling two measures induce the same probability distribution on order types, then these measures are projectively equivalent provided the support of at least one of them has non-empty interior. We also show that some condition on the Hausdorff dimension of the support is necessary to obtain projective rigidity and we construct limits of order types that cannot be represented by a planar measure. Returning to combinatorial geometry we relate the regularity of this analytic representation to the aforementioned problem of Erdős on the density of k-tuples in convex position, for large k.

Keywords: Limits of structures, flag algebra, geometric measure theory, Erdős-Szekeres theorem, Sylvester’s problem.

1 Introduction

The theory of dense graph limits, developed over the last decade by Borgs, Chayes, Lovász, Razborov, Sós, Szegedy, Vesztergombi and others, studies sequences of large graphs using a combination of equivalent formalisms: algebraic (as positive homomorphisms from certain graph algebras into \( \mathbb{R} \)), analytic (as measurable, symmetric functions from \([0,1]^2\) to \([0,1]\) called graphons) and discrete probabilistic (as families \( \{D_n\} \) of probability distributions over \( n \)-vertex graphs satisfying certain relations). These viewpoints are complementary: while the algebraic formalism allows effective computations via semi-definite methods \([30]\), the analytic viewpoint offers powerful methods (norm equivalence, completeness) to treat in a unified setting a diversity of graph problems such as pseudorandom graphs or property testing \([25]\).

In this article, we combine ideas from dense graph limits with order types, which are combinatorial structures arising in geometry. The order type of a point set encodes the respective positions of its elements, and suffices to determine many of its properties, for instance its convex hull, its triangulations, or which graphs admit crossing-free straight line drawings with vertices supported on that point set. Order types have received continued attention in discrete and computational geometry since the 1980s

*This work was partially supported by ANR blanc PRESAGE (ANR–11-BS02–003).
†Université de Lorraine, CNRS, INRIA, LORIA, F-54000, Nancy, France. Email: xavier.goaoc@loria.fr. This author was partially supported by Institut Universitaire de France.
‡Université Paris Est, LIGM (UMR 8049), CNRS, ENPC, ESIEE, UPEM, F-77454, Marne-la-Vallée, France. Email: alfredo.hubard@u-pem.fr.
§Radboud University Nijmegen, Netherlands. Email: r.deverclos@math.ru.nl.
¶Centre National de la Recherche Scientifique, ICube (CSTB), Strasbourg, France. Email: sereni@kam.mff.cuni.cz.
∥Department of Mathematics, Emory University, Atlanta, USA. Email: jan@ucw.cz. This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 800697. Previous affiliation: Department of Mathematics and Statistics, McGill University, Montreal, Canada, where this author was supported by CRM-ISM fellowship.

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and are known to be rather intricate objects, difficult to axiomatise [33]. While order types are well defined in a variety of contexts (arbitrary dimensions, abstractly via the theory of oriented matroids) all point sets considered in this work are finite subsets of the Euclidean plane with no aligned triple, unless otherwise specified.

1.1 Order types and their limits

Let us first define our main objects of study.

Order types. Define the orientation of a triangle $pqr$ in the plane to be clockwise (CW) if $r$ lies to the right of the line $pq$ oriented from $p$ to $q$ and counter-clockwise (CCW) if $r$ lies to the left of that oriented line. (So the orientation of $qpr$ is different from that of $pqr$.) We say that two planar point sets $P$ and $Q$ have the same order type if there exists a bijection $f : P \rightarrow Q$ that preserves orientations: for any triple of pairwise distinct points $p,q,r \in P$ the triangles $pqr$ and $f(p)f(q)f(r)$ have the same orientation. The relation of having the same order type is easily checked to be an equivalence relation; the equivalence class, for this relation, of a finite point set $P$ is called the order type of $P$. A point set $P$ with order type $\omega$ is called a realization of $\omega$.

When convenient, we extend to order types any notion that can be defined on a set of points and does not depend on a particular choice of realization. For instance we define the size of an order type $\omega$ to be the cardinality $|\omega|$ of any of its realizations. We adopt the convention that there is exactly one order type of each of the sizes 0, 1 and 2. We let $O$ be the set of order types and $O_n$ the set of order types of size $n$.

Convergent sequences and limits of order types. We define the density $p(\omega,\omega')$ of an order type $\omega$ in another order type $\omega'$ as the probability that $|\omega|$ random points chosen uniformly from a point set realizing $\omega'$ have order type $\omega$. (Observe that this probability depends solely on the order types and not on the choice of realization.) We say that a sequence $(\omega_n)_{n \in \mathbb{N}}$ of order types converges if the size $|\omega_n|$ goes to infinity as $n$ goes to infinity, and for any fixed order type $\omega$ the sequence $(p(\omega,\omega_n))_n$ of densities converges. The limit of a convergent sequence of order types $(\omega_n)_{n \in \mathbb{N}}$ is the map

$$\left\{ \begin{array}{ll} O & \rightarrow [0,1] \\ \omega & \mapsto \lim_{n \rightarrow \infty} p(\omega,\omega_n) \end{array} \right.$$  

A standard compactness argument reveals that limits of order types abound. Indeed, for each element $\omega_n$ in a sequence of order types, the map $\omega \in O \mapsto p(\omega,\omega_n)$ can be seen as a point in $[0,1]^{O_n}$, which is compact by Tychonoff’s theorem. Any sequence of order types with sizes going to infinity therefore contains a convergent subsequence.

1.2 Problems and results

We explore the application of the theory of limits of dense graphs to order types in two directions. On one hand, the algebraic description of limits as positive homomorphisms of flag algebras makes these limits amenable to semi-definite programming methods. We implemented this approach for order types and obtained numerical results. On the other hand, the fact that measures generally define limits of order types (Corollary 8) unveils stimulating problems and interesting questions, of a more structural nature, on the relation between measures and limits of order types.

Flag algebras of order types. The starting motivation for our work is a question raised by Erdős and Guy [18] in 1973 (see also [17]): “what is the minimum number $\text{conv}_k(n)$ of convex $k$-gons in a set of $n$ points in the plane?”. This falls within the scope of a general (and more conceptual than precise) question of Sylvester: “what is the probability that four points at random are in convex position?”. Making sense of Sylvester’s question implies defining a distribution on 4-tuples of points, and from the beginning of the 20th century several variants using distributions coming from the theory of convex sets were investigated (e.g. uniform or gaussian distributions on compact convex sets). For more background on this, the reader is referred to the survey by Ábrego, Fernández-Merchant & Salazar [4] and to the book
by Brass, Moser & Pach [11, Section 8]. We also point out that Sylvester’s question is actually related to several important conjectures in convex geometry [12, Chapter 3]. By a standard double-counting argument, one sees that $\text{conv}_k(n+1) \geq \frac{n+1}{n+2} \cdot \text{conv}_k(n)$, so the limiting density

$$c_k = \lim_{n \to \infty} \frac{\text{conv}_k(n)}{\binom{n}{k}}$$

is well defined and equal to the supremum of this ratio for $n \in \mathbb{N}$. We apply the framework of flag algebras to order types and use the semi-definite method to obtain lower bounds on $c_k$ for $k \in \{4, 5, 6\}$.

As it turns out, the literature around the computation of $c_4$ is vast: not only does $c_4$ correspond to the last open case of a relaxation of Sylvester’s conjecture to all open sets of finite area, but as discovered by Scheinerman and Wilf [32], its value is determined by the asymptotic behaviour of the rectilinear crossing number of the complete graph, which has been extensively investigated. For this particular case, the best lower bound we could obtain is $c_4 \geq 0.37843917$, which falls short of the currently best known lower bound, namely $277/729 > 0.3799$. This better lower bound is obtained by plugging results of Aichholzer et al. [6] and Ábrego et al. [1, 3] into an expression of the rectilinear crossing number found independently by Lovász et al. [27] and by Ábrego and Fernández-Merchant [2]. The best currently known upper bound on $c_4$ is $c_4 < 0.380473$, and is due to Fabila-Monroy and López [20]. Nonetheless, our method allows us to strongly improve the known lower bounds on $c_5$ and on $c_6$.

**Proposition 1.** We have $c_5 \geq 0.0608516$ and $c_6 \geq 0.0018311$.

To the best of our knowledge, prior to this work the only known lower bounds on any constant $c_k$ with $k \geq 5$ followed from a general and important result of Erdős and Szekeres [19], via a simple double counting argument. One indeed sees that $c_5 \geq \frac{554}{27} > 0.0793$ using that nine points in the plane must contain a convex pentagon (a result attributed to Makai by Erdős and Szekeres [19], the first published proof being by Kalbfleisch, Kalbfleisch & Stanton [23]). Similarly, as Szekeres and Peters [38] proved (using a computer-search) that the Erdős-Szekeres conjecture [19] is true for convex hexagons, one can use that seventeen points in the plane must contain a convex hexagon to infer that $c_6 \geq \frac{1160}{67} > 0.000808$. The best upper bounds that we are aware of on these numbers are $c_5 \leq 0.0625$ and $c_6 \leq 0.005822$. We point out that Ábrego (personal communication) conjectured that $c_5 = 0.0625$. We again refer the interested reader to the survey and the book cited above [4, 11].

We prove Proposition 1 by a reformulation of limits of order types as positive homomorphisms from a so-called flag algebra of order types into $\mathbb{R}$ (see Proposition 9); this point of view allows a semidefinite programming formulation of the search for inequalities satisfied by limits of order types. Specifically, we argue that for any limit of order types $\ell$

$$\ell(\omega_k) \geq 0.0608516 \quad \text{and} \quad \ell(\omega_6) \geq 0.0018311,$$

where $\omega_k$ is the order type of $k$ points in convex position for any positive integer $k$.

On a related topic, we can mention a recent application of flag algebras by Balogh, Liédický, and Salazar [9] to the (non rectilinear) crossing number of the complete graph. Their techniques differ from ours in that they use rotational systems instead of order types, and they use results about the crossing number of the complete graph for small numbers.

We now turn to another aspect of our work using flag algebras of order types. Probabilistic constructions often present extremal combinatorial properties that are beyond our imagination, a textbook example being the lower bound on Ramsey numbers for graphs devised by Erdős [16] in 1947. Sampling order types of a given size uniformly is of much interest to test conjectures and search for extremal examples (see e.g. [11, p. 326]). However the uniform distribution on order types seems out of reach as suggested by the lack of closed formulas for counting them, or heuristics to generate them, but we know of no formal justification of the hardness of approximation of this distribution. As it turns out, limits of order types can also be defined as families of probability distributions on order types with certain internal consistencies (see Proposition 7) and we exploit this interpretation to provide negative results on certain sampling strategies. Our second result obtained by the semidefinite method of flag algebras indeed shows that a broad class of random generation methods must exhibit some bias.

**Proposition 2.** For any limit of order types $\ell$ there exist two order types $\omega_1$ and $\omega_2$ of size 6 such that $\ell(\omega_1) > 1.8208 \ell(\omega_2)$. 

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This unavoidable bias holds, in particular, for the random generation of order types by independent sampling of points from any finite Borel measure over $\mathbb{R}^2$, see Corollary 8.

**Representing limits by measures.** Given a finite Borel measure $\mu$ over $\mathbb{R}^2$ and an order type $\omega \in \mathcal{O}$, let $\ell_\mu(\omega)$ be the probability that $|\omega|$ random points sampled independently from $\mu$ have order type $\omega$. It turns out (Corollary 8) that $\ell_\mu$ is a limit of order types if and only if every line is negligible for $\mu$. Going in the other direction, it is natural to wonder if geometric measures could serve as analytic representations of limits of order types, like graphons for limits of dense graphs. This raises several questions, here are some that we investigate: does every limit of order types enjoy such a realization? For those which do, what does the set of measures realizing them look like? In analogy with the study of realization spaces of order types [8, 14, 24, 33] we investigate how the weak topology on probability measures relates to the topology on limits.

We provide an explicit construction of a limit of order types that cannot be represented by any measure in the plane. For $t \in (0, 1)$ let $\circ_t$ be the probability distribution over $\mathbb{R}^2$ supported on two concentric circles with radii 1 and $t$, respectively, where each of the two circles has $\circ_t$-measure 1/2, distributed proportionally to the length on this circle. Because every line is negligible for $\circ_t$, Corollary 8 ensures that $\ell_{\circ_t}$ is a limit of order types. We define $\ell_{\circ}$ to be the limit of an arbitrary convergent sub-sequence of $(\ell_{\circ_{1/n}})_{n \in \mathbb{N}}$.

**Proposition 3.** There exists no probability measure $\mu$ such that $\ell_\mu = \ell_{\circ}$.

The proof of Proposition 3 reveals that the sequence $(\ell_{\circ_{1/n}})_{n \in \mathbb{N}}$ is in fact convergent, so $\ell_{\circ}$ is indeed an explicit example. Actually, an explicit description (for instance based on the reformulation of $\ell_{\circ}$ used in the proof of Lemma 3.6) is possible, if tedious.

Let us now turn our attention to a family of limits that has a particularly nice realization space. Firstly, observe that nonsingular affine transforms preserve order types. Thus, if $\mu$ is a measure that does not charge any line, $f$ is a nonsingular affine transform, and $\mu' = \mu \circ f^{-1}$ is the push-forward of $\mu$ by $f$, then $\ell_{\mu'} = \ell_\mu$. More generally, one can take $f$ to be the restriction to $\mathbb{R}^2$ of an “adequate” projective map (we spell out the meaning of “adequate” in Section 3.1). Our main contribution in this direction is a projective rigidity result: we show that under natural measure theoretic conditions on $\mu$, the realization space of $\mu$ is essentially a point.

**Theorem 4.** Let $\mu_1$ and $\mu_2$ be two compactly supported measures of $\mathbb{R}^2$ that charge no line and whose supports have non-empty interiors. If $\ell_{\mu_1} = \ell_{\mu_2}$, then there exists a projective transformation $f$ such that $\mu_2 \circ f = \mu_1$.

The converse of the statement of Theorem 4 is not true: it can fail for instance if the line mapped to infinity intersects the interior of $\text{supp} \mu$. The approach we use to establish it actually provides a necessary and sufficient condition, expressed in terms of “spherical transforms” as defined in Section 3.1. The third author conjectured [13] that the condition on $\mu$ can be weakened.

**Conjecture 5.** If $\mu$ is a measure that charges no line and has support of Hausdorff dimension strictly greater than 1, then every measure that realizes $\ell_\mu$ is projectively equivalent to $\mu$.

It is easy to see that the conditions in Conjecture 5 are necessary. Recalling that $\omega_k$ is the order type of $k$ points in convex position, the limit of order types that for every $k$ gives probability 1 to $\omega_k$ can be realized by measures of Hausdorff dimension in $(0, 1)$. In particular, these are pairwise projectively inequivalent. More interestingly, we build a limit of order types $\ell_E$ presenting projective flexibility, and which is interesting from the combinatorial geometry perspective: indeed, $\ell_E$ is a nearly optimal lower bound for the aforementioned problem of Erdős, witnessing that $\log c_k = \Theta(-k^2)$.

**Theorem 6.** There exists a limit of order types $\ell_E$ that can be realized by a measure of Hausdorff dimension $s$ for any $s \in (0, 1)$ for which $\ell_E(\omega_k) = 2^{-\frac{k^2}{2}} + O(k \log k)$. Furthermore, $\ell_E$ cannot be realized by a measure that is absolutely continuous with respect to the Lebesgue measure.

As in the rigidity result, the relation to the Hausdorff dimension seems fundamental: we observe that regular measures present a very different asymptotic behavior with respect to the density of $\omega_k$. 

4
2 Flag algebras

2.1 Reformulation of limits

Order types can be understood as equivalence classes of chirotopes under the action of permutations (see below). As such, they form an example of a model in the language of Razborov [30], and the theory of limits of order types is a special case of Razborov’s work. This section provides a self-contained presentation of the probabilistic and algebraic reformulations of limits of order types.

2.1.1 Probabilistic characterization

Let \((\omega_n)_{n \in \mathbb{N}}\) be a sequence of order types converging to a limit \(\ell\). Let \(\omega \in \mathcal{O}\), let \(k \geq |\omega|\) and let \(n_0\) be large enough so that \(|\omega_n| \geq k\) for every \(n \geq n_0\). A simple conditioning argument yields that for any \(n \geq n_0\),

\[
p(\omega, \omega_n) = \sum_{\omega' \in \mathcal{O}_k} p(\omega, \omega') p(\omega', \omega_n).
\]

Indeed, the probability that a random sample realizes \(\omega\) is the same if we sample uniformly \(|\omega|\) points from a realization of \(\omega_n\), or if we first sample \(k\) points uniformly from that realization and next uniformly select a subset of \(|\omega|\) of these \(k\) points. It follows that any limit \(\ell\) of order types satisfies the following conditioning identities:

\[
\forall \omega \in \mathcal{O}, \forall k \geq |\omega|, \quad \ell(\omega) = \sum_{\omega' \in \mathcal{O}_k} p(\omega, \omega') \ell(\omega'). \tag{2}
\]

As one notices, Equation (1) yields that the conditioning identities are equivalent to the (seemingly weaker) condition

\[
\forall \omega \in \mathcal{O}, \quad \ell(\omega) = \sum_{\omega' \in \mathcal{O}_{|\omega|+1}} p(\omega, \omega') \ell(\omega'). \tag{3}
\]

However, a stronger condition than Equation (2) is needed to characterize limits of order types, as we illustrate in Example 2.1. The split probability \(p(\omega', \omega''; \omega)\), where \(\omega', \omega''\) and \(\omega\) are order types, is the probability that a random partition of a point set realizing \(\omega\) into two classes of sizes \(|\omega'|\) and \(|\omega''|\), chosen uniformly among all such partitions, produces two sets with respective order types \(\omega'\) and \(\omega''\). (In particular \(p(\omega', \omega''; \omega) = 0\) if \(|\omega| \neq |\omega'| + |\omega''|\).) We provide a detailed proof of the following proposition, but the reader familiar with the topic already sees the corresponding result for dense graph limits [26, Theorem 2.2].

**Proposition 7.** A function \(\ell: \mathcal{O} \to \mathbb{R}\) is a limit of order types if and only if

\[
\forall \omega', \omega'' \in \mathcal{O}, \quad \ell(\omega') \ell(\omega'') = \sum_{\omega \in \mathcal{O}_{|\omega'|+|\omega''|}} p(\omega', \omega''; \omega) \ell(\omega), \tag{4}
\]

and for every \(n \in \mathbb{N}\), the restriction \(\ell|_{\mathcal{O}_n}\) is a probability distribution on \(\mathcal{O}_n\).

Before establishing Proposition 7, let us first point out that the product condition (4) implies the conditioning condition (2), as is seen by taking for \(\omega''\) the (unique) order type of size 1.

**Proof of Proposition 7.** We start by establishing the direct implication. The fact that \(\ell|_{\mathcal{O}_n}\) is a probability distribution on \(\mathcal{O}_n\) follows from the definition of a limit. As for Equation (4), fix two order types \(\omega'\) and \(\omega''\) in \(\mathcal{O}\). Let \(\omega_n\) be a random order type sampled from \(\ell|_{\mathcal{O}_n}\) where \(n \geq |\omega'| + |\omega''|\). Let

\[
\alpha_n = p(\omega', \omega_n) p(\omega'', \omega_n) \quad \text{and} \quad \beta_n = \sum_{\omega \in \mathcal{O}_{|\omega'|+|\omega''|}} p(\omega', \omega''; \omega) p(\omega, \omega_n).
\]

Now, fix some point set \(P\) with order type \(\omega_n\). By the definition, the value \(p(\omega, \omega_n)\) is the probability that \(|\omega|\) points sampled uniformly from \(P\) have order type \(\omega\). Now, on one hand, \(\alpha_n\) equals the probability that two independent events both happens: (i) that a set \(P'\) of \(|\omega'|\) random points chosen uniformly from \(P\) has order type \(\omega'\), and (ii) that another set \(P''\) of \(|\omega''|\) random points chosen uniformly from \(P\) has order type \(\omega''\). On the other hand, observe that \(\beta_n\) equals the probability that (i) and (ii) happen and...
that \( P' \) and \( P'' \) are disjoint. The difference \( |\alpha - \beta| \) is therefore bounded from above by the probability that \( P' \) and \( P'' \) intersect. Bounding from above the probability that \( P' \) and \( P'' \) have an intersection of one or more elements by the expected size of \( P' \cap P'' \) yields that

\[
|p(\omega', \omega) - \sum_{\omega \in \mathcal{O}, |\omega'| = |\omega'|} p(\omega', \omega') p(\omega, \omega')| \leq E(|P' \cap P'')| = \frac{|\omega'| |\omega'|}{|\omega'|}.
\] (5)

Taking \( n \to \infty \) in (5) we see that \( \ell \) satisfies Equation (4).

Conversely, suppose that \( \ell \) satisfies both conditions. For every integer \( n \), we pick a random order type \( r_n \) of size \( n^2 \) according to \( \ell_{|\mathcal{O}|} \). We assert that

\[
\forall \omega \in \mathcal{O}, \quad P\left( \lim_{n \to \infty} p(\omega, r_n) \neq \ell(\omega) \right) = 0.
\]

Since the number of order types is countable, we conclude that the random sequence \( (r_n)_{n \in \mathbb{N}} \) is convergent and has limit \( \ell \) with probability 1.

It remains to prove the assertion. Fix some \( \omega \in \mathcal{O} \) and assume that \( n \geq |\omega| \). Then

\[
E[p(\omega, r_n)] = \sum_{\omega' \in \mathcal{O}_{n^2}} P(r_n = \omega') p(\omega, \omega') = \sum_{\omega' \in \mathcal{O}_{n^2}} \ell(\omega') p(\omega, \omega') = \ell(\omega),
\]

and

\[
\text{Var}(p(\omega, r_n)) = E[p(\omega, r_n)^2] - E[p(\omega, r_n)]^2 = \sum_{\omega' \in \mathcal{O}_{n^2}} p(\omega, \omega')^2 \ell(\omega') - \ell(\omega)^2.
\]

By Equation (4),

\[
\text{Var}(p(\omega, r_n)) = \sum_{\omega' \in \mathcal{O}_{n^2}} p(\omega, \omega')^2 \ell(\omega') - \sum_{\omega'' \in \mathcal{O}_{|\omega|}} p(\omega, \omega'') \ell(\omega '').
\]

Since \( 2|\omega| \leq n^2 = |r_n| \), Equation (2) yields that \( \ell(\omega '') = \sum_{\omega' \in \mathcal{O}_{n^2}} p(\omega ', \omega') \ell(\omega ') \). So we deduce that

\[
\text{Var}(p(\omega, r_n)) = \sum_{\omega' \in \mathcal{O}_{n^2}} \left( p(\omega, \omega')^2 - \sum_{\omega'' \in \mathcal{O}_{|\omega|}} p(\omega, \omega'; \omega'') p(\omega', \omega') \right) \ell(\omega').
\]

We observe that Inequality (5) obtained above is valid in general, and therefore

\[
\text{Var}(p(\omega, r_n)) \leq \sum_{\omega' \in \mathcal{O}_{n^2}} |\omega|^2 \ell(\omega') = \frac{|\omega|^2}{n^2}.
\]

By Chebyshev’s inequality it thus follows that for any positive \( \varepsilon \),

\[
P(|p(\omega, r_n) - \ell(\omega)| > \varepsilon) \leq \frac{|\omega|^2}{\varepsilon^2 n^2}.
\]

Therefore, for any \( \omega \) and \( \varepsilon > 0 \), the sum \( \sum_{n \geq 1} P(|p(\omega, r_n) - \ell(\omega)| > \varepsilon) \) is finite and hence the Borel-Cantelli lemma implies that with probability 1, only finitely many of the events \( \{|p(\omega, r_n) - \ell(\omega)| > \varepsilon\} \) happen. Consequently, it holds with probability 1 that \( \lim_{n \to \infty} p(\omega, r_n) = \ell(\omega) \). \( \square \)

Proposition 7 provides many examples of limits of order types.

Corollary 8. Let \( \mu \) be a finite Borel measure over \( \mathbb{R}^2 \). The map \( \ell_\mu : \omega \in \mathcal{O} \mapsto p(\omega, \mu) \) is a limit of order types if and only every line is negligible for \( \mu \).

Proof. Assume that \( \ell_\mu \) is a limit of order types and let \( (\omega_n)_{n \in \mathbb{N}} \) be a sequence converging to \( \mu \). Let \( \cdot \) be the order type of size 3. We have

\[
p(\cdot, \mu) = \ell_\mu(\cdot) = \lim_{n \to \infty} p(\cdot, \omega_n) = 1,
\]

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so three random points chosen independently from \( \frac{1}{\mu(R^2)} \mu \) are aligned with probability 0, and consequently every line is negligible for \( \mu \).

Conversely, assume that \( \mu \) is a measure for which every line is negligible. For every integer \( n \geq 3 \) the restriction of \( \ell_{\mu} \) to \( \mathcal{O}_n \) is a probability distribution. Moreover, for every order type \( \omega \in \mathcal{O} \) and every integer \( m > |\omega| \), we have

\[
\ell_{\mu}(\omega) = \sum_{\omega' \in \mathcal{O}_m} p(\omega, \omega') \ell_{\mu}(\omega')
\]

by sampling \( m \) points from \( \mu \) and sub-sampling \( |\omega| \) points among them uniformly. Proposition 7 then implies that \( \ell_{\mu} \) is a limit of order types.

We conclude this section with a simple example of a function \( \ell \) that is not a limit of order types, and yet satisfies the conditioning identities and restricts on every \( \mathcal{O}_n \) to a probability distribution.

**Example 2.1.** Let \( \ell_0 \) be the limit where convex order types have probability 1. Let \( \ell_\odot \) be the limit defined before Proposition 3 on page 4. Set \( \ell \) to be \( \frac{1}{2} (\ell_0 + \ell_\odot) \).

First, note that if \( \ell_1 \) and \( \ell_2 \) are two limits of order types and \( \ell_3 \) is any convex combination of \( \ell_1 \) and \( \ell_2 \), then the conditioning identities for \( \ell_1 \) and \( \ell_2 \) ensure that:

\[
\forall \omega \in \mathcal{O}, \forall k > |\omega|, \quad \ell_3(\omega) = \sum_{\omega' \in \mathcal{O}_k} p(\omega, \omega') \ell_3(\omega').
\]

In particular, our function \( \ell \) satisfies the conditioning identities. Similarly, it is immediate to check that for every \( n \), the restriction of \( \ell \) to \( \mathcal{O}_n \) is a probability distribution on \( \mathcal{O}_n \).

We show that \( \ell \) does not satisfy (4) by proving that

\[
\ell \left( \begin{array}{c} \vdots \\ \vdots \\ \dfrac{1}{32} \end{array} \right) \ell(\bullet) = \frac{1}{32} \quad \text{and} \quad \sum_{|\omega|=5} p \left( \begin{array}{c} \vdots \\ \vdots \\ \bullet ; \omega \end{array} \right) \ell(\omega) = \frac{3}{64}.
\]

To establish these equalities, we compute certain values of \( \ell_\odot \), which essentially boils down to computing two probabilities: (i) that the number of points on the outer circle equals that of the convex hull of the order type considered, and (ii) that the convex hull of these “outer points” contains the centre of the circle.

To compute (ii) requires to compute the probability that \( k \) points chosen uniformly on a circle have the circle’s center in their convex hull. Let us condition on the \( k \) lines formed by the points and the center of the circle (the lines being almost surely pairwise distinct). Each point is selected uniformly from the two possible, antipodal, positions on the corresponding line, and the initial choice of the lines does not matter. So the probability reformulates as: given \( k \) pairs of antipodal points on the circle, how many of the \( 2^k \) \( k \)-gons formed by one point from each pair contain the center? For \( k = 3 \) the answer is 2 out of 8 configurations, while for \( k = 4 \) the answer is 8 out of 16 configurations. We thus infer that

\[
\ell_\odot \left( \begin{array}{c} \vdots \\ \vdots \\ \dfrac{1}{2^k} \end{array} \right) = \frac{1}{2^k} \quad \text{and} \quad \ell_\odot \left( \begin{array}{c} \vdots \\ \vdots \\ \dfrac{1}{2^k} \end{array} \right) = \frac{5}{2^k} \frac{1}{2^k} = \frac{5}{64},
\]

and

\[
\ell_\odot \left( \begin{array}{c} \vdots \\ \vdots \\ \dfrac{1}{2^k} \end{array} \right) = \frac{5}{2^k} \frac{1}{2} = \frac{5}{64}.
\]

It follows, on one hand, that

\[
\ell \left( \begin{array}{c} \vdots \\ \vdots \\ \dfrac{1}{2^k} \end{array} \right) \ell(\bullet) = \frac{1}{2} \left( \ell_\odot \left( \begin{array}{c} \vdots \\ \vdots \\ \dfrac{1}{2^k} \end{array} \right) + \ell_\odot \left( \begin{array}{c} \vdots \\ \vdots \\ \dfrac{1}{2^k} \end{array} \right) \right) = \frac{1}{2} \left( 0 + \frac{1}{16} \right) = \frac{1}{32},
\]

and on the other hand, that

\[
\sum_{|\omega|=5} p \left( \begin{array}{c} \vdots \\ \vdots \\ \bullet ; \omega \end{array} \right) \ell(\omega) = \frac{4}{5} \ell \left( \begin{array}{c} \vdots \\ \vdots \\ \dfrac{1}{2^k} \end{array} \right) + \frac{2}{5} \ell \left( \begin{array}{c} \vdots \\ \vdots \\ \dfrac{1}{2^k} \end{array} \right) + 0 \ell \left( \begin{array}{c} \vdots \\ \vdots \\ \dfrac{1}{2^k} \end{array} \right)
\]

\[
= \frac{2}{5} \ell_\odot \left( \begin{array}{c} \vdots \\ \vdots \\ \dfrac{1}{2^k} \end{array} \right) + \frac{1}{5} \ell_\odot \left( \begin{array}{c} \vdots \\ \vdots \\ \dfrac{1}{2^k} \end{array} \right)
\]

\[
= \frac{2}{5} \times \frac{5}{64} + \frac{1}{5} \times \frac{5}{64}
\]

\[
= \frac{3}{64} \neq \ell \left( \begin{array}{c} \vdots \\ \vdots \\ \dfrac{1}{2^k} \end{array} \right) \ell(\bullet).
\]
2.1.2 Algebraic characterization

Recall that by (2) every limit $\ell$ of order types satisfies
\[ \forall \omega \in \mathcal{O}, \forall k \geq |\omega|, \quad \ell(\omega) = \sum_{\omega' \in \mathcal{O}_k} p(\omega, \omega') \ell(\omega'). \]

Now, let $\mathbb{R}\mathcal{O}$ be the set of all finite formal linear combinations of elements of $\mathcal{O}$ with real coefficients and consider the quotient vector space
\[ \mathcal{A} = \mathbb{R}\mathcal{O} / \mathcal{K} \]
where $\mathcal{K} = \text{vect}\{\omega - \sum_{\omega' \in \mathcal{O}_{|\omega|+1}} p(\omega, \omega') \omega' : \omega \in \mathcal{O}\}$. We define a product on $\mathcal{O}$ as follows:
\[ \forall \omega_1, \omega_2 \in \mathcal{O}, \quad \omega_1 \times \omega_2 = \sum_{\omega \in \mathcal{O}_{|\omega_1|+|\omega_2|}} p(\omega_1, \omega_2; \omega) \omega, \quad (6) \]
and we extend it linearly to $\mathbb{R}\mathcal{O}$. This extension is compatible with the quotient by $\mathcal{K}$ and therefore turns $\mathcal{A}$ into an algebra [30, Lemma 2.4].

An algebra homomorphism from $\mathcal{A}$ to $\mathbb{R}$ is positive if it maps every element of $\mathcal{O}$ to a non-negative real, and we define $\text{Hom}^+(\mathcal{A}, \mathbb{R})$ to be the set of positive algebra homomorphisms from $\mathcal{A}$ to $\mathbb{R}$. Observe that any algebra homomorphism sends $\cdot$, the order-type of size one, to the real 1 as $\cdot$ is the neutral element for the product of order types.

**Proposition 9** ([30, Theorem 3.3b]). A map $f : \mathcal{O} \to \mathbb{R}$ is a limit of order types if and only if its linear extension is compatible with the quotient by $\mathcal{K}$ and defines a positive homomorphism from $\mathcal{A}$ to $\mathbb{R}$.

We equip $\mathcal{A}$ with a partial order $\geq$, and write that $a_1 \geq a_2$ with $a_1, a_2 \in \mathcal{A}$ if the image of $a_1 - a_2$ under every positive homomorphism is non-negative. The algebra $\mathcal{A}$ allows us to compute effectively with density relations that hold for every limit $\ell$.

**Example 2.2.** Let $\cdot$ be the order type on one point, $\cdot : :$ and $\cdot : : :$ the two order types of size four and $\cdot : : : :$, $\cdot : : : : :$ and $\cdot : : : : : :$, the three order types of size five, seen as elements of $\mathcal{A}$. It follows from the definitions and from Equation (2) that
\[ \cdot : : = \cdot : + \frac{3}{5} \cdot : : + \frac{1}{5} \cdot : : : \quad \text{and} \quad \cdot : : : = \cdot : : + \cdot : : : + \cdot : : : : . \quad (7) \]
Since for any limit of order types $\ell$ we have $\ell(\cdot) = 1$, the above implies that
\[ \ell(\omega_4) = \ell \left( \frac{1}{5} \cdot : : + \frac{1}{5} \cdot : : : + \frac{1}{5} \cdot : : : : \right) + \ell \left( \frac{4}{5} \cdot : : : + \frac{2}{5} \cdot : : : : \right) \geq \frac{1}{5} \ell(\cdot) = \frac{1}{5} \]
Using again Equation (2), and the non-negativity of $\cdot : : : :$, we obtain
\[ \frac{2}{5} \cdot : : : \geq \cdot : : : - \frac{3}{5} (\cdot : : + \cdot : : : + \cdot : : : : ) = \cdot : : : - \frac{3}{5} \]
and $\ell(\omega_5) \geq \frac{5}{2} \ell(\omega_4) - \frac{3}{2}$ for any limit of order types $\ell$.

2.1.3 Semi-definite method

Proposition 9 allows to search for inequalities over $\mathcal{A}$ by semidefinite programming. Let us give an intuition of how this works on an example. Here, we use the comprehensive list of all the order types of size up to 11, which was made available by Aichholzer [1] based on his work with Aurenhammer and Krasser [5] on the enumeration of order types. Throughout this paper, all non-trivial facts we use without reference on order types of small size can be traced back to that resource.

\[^1\text{http://www.ist.tugraz.at/aichholzer/research/rp/triangulations/ordertypes/}\]
Example 2.3. A simple (mechanical) examination of the 6405 order types of size 8 reveals that 
\( p(\sigma_4, \omega) \geq 19/70 \) for any \( \omega \in \mathcal{O}_8 \). With Identity (2) this implies that \( \cdots \geq 19/70 \) or equivalently that 
\( c_4 \geq 19/70 > 0.2714 \). Observe that for any \( C \in \mathcal{A} \) and any (linear extension of a) limit of order types \( \ell \) we have \( \ell(C \times C) = \ell(C)^2 \geq 0 \) by Proposition 9. We thus have at our command an infinite source of inequalities to consider to try and improve the above bounds. For instance, a tedious but elementary computation yields that
\[
\left( \frac{6}{25} \cdots - \frac{11}{125} \cdots \right)^2 + \frac{298819}{1093750} \sum_{\omega \in \mathcal{O}_8} \omega = \sum_{\omega \in \mathcal{O}_8} a_\omega \omega,
\]
where \( a_\omega \leq p(\sigma_4, \omega) \) for every \( \omega \in \mathcal{O}_8 \). This implies that \( p(\sigma_4) \geq 298819/1093750 > 0.2732 \) for any limit of order types \( \ell \). The search for interesting combinations of such inequalities can be done by semidefinite programming.

2.2 Improving the semidefinite method via rooting and averaging

The effectiveness of the semidefinite method for limits of graphs was greatly enhanced by considering partially labelled graphs. We unfold here a similar machinery, using some blend of order types and chirotopes.

**Partially labelled point sets, flags, \( \sigma \)-flags and \( \mathcal{A}^\sigma \).** A point set partially labelled by a finite set \( \mathcal{Z} \) (the labels) is a finite point set \( P \) together with some injective map \( L: \mathcal{Z} \to P \). It is written \( (P, \mathcal{Z}, L) \) when we need to make explicit the set of labels and the label map. Two partially labelled point sets \( (P, \mathcal{Z}, L) \) and \( (P', \mathcal{Z}, L') \) have the same flag if there exists a bijection \( \phi: P \to P' \) that preserves both the orientation and the labelling, the latter meaning that \( \phi(L(i)) = L'(i) \) for each \( i \in \mathcal{Z} \). The relation of having the same flag is an equivalence relation, and a flag is an equivalence class for this relation. Again, we call any partially labelled point set a realization of its equivalence class, and the size \( |\tau| \) of a flag \( \tau \) is the cardinality of any of its realizations.

A flag where all the points are labelled, i.e. where \( |P| = |\mathcal{Z}| \) in some realization \( (P, \mathcal{Z}, L) \), is a \( \mathcal{Z} \)-chirotope. (When \( \mathcal{Z} = \{k\} = \{1, 2, \ldots, k\} \) a \( \mathcal{Z} \)-chirotope coincides with the classical notion of chirotope.) Note that chirotopes correspond to types in the flag algebra terminology. Discarding the non-labelled part of a flag \( \tau \) with label set \( \mathcal{Z} \) yields some \( \mathcal{Z} \)-chirotope \( \sigma \) called the root of \( \tau \). A flag with root \( \sigma \) is a \( \sigma \)-flag and by \( \mathcal{A}^\sigma \) we mean the set of \( \sigma \)-flags. The unlabelling \( \tau^\emptyset \) of a flag \( \tau \) with realization \( (P, \mathcal{Z}, L) \) is the order type of \( P \).

Let \( \mathcal{Z} \) be a set of labels and \( \sigma \) a \( \mathcal{Z} \)-chirotope. We define densities and split probabilities for \( \sigma \)-flags like for order types. Namely, let \( \tau \), \( \tau^\prime \), and \( \tau'' \) be \( \sigma \)-flags respectively realized by \( (P, \mathcal{Z}, L) \), \( (P', \mathcal{Z}, L') \) and \( (P'', \mathcal{Z}, L'') \). The density of \( \tau \) in \( \tau^\prime \) is the probability that for a random subset \( S \) of size \( |P| - |\mathcal{Z}| \), chosen uniformly in \( P'' \setminus L''(\mathcal{Z}) \), the partially labelled set \( (S \cup L''(\mathcal{Z}), \mathcal{Z}, L'') \) has flag \( \tau \). The split probability \( p(\tau, \tau', \tau'') \) is the probability that for a random subset \( S \) of size \( |P| - |\mathcal{Z}| \), chosen uniformly in \( P'' \setminus L''(\mathcal{Z}) \), the partially labelled sets \( (S \cup L''(\mathcal{Z}), \mathcal{Z}, L'') \) and \( (P'' \setminus S, \mathcal{Z}, L'') \) have respective flags \( \tau \) and \( \tau' \).

We can finally define an algebra of \( \sigma \)-flags as for order types. We endow the quotient vector space
\[
\mathcal{A}^\sigma = \mathcal{R}\mathcal{X}^\sigma / \mathcal{R}^\sigma
\]
where
\[
\mathcal{R}^\sigma = \text{vect}\left\{ \omega - \sum_{\omega' \in \mathcal{X}_{|\sigma|+1}^\sigma} p(\omega, \omega')\omega' : \omega \in \mathcal{X}^\sigma \right\}
\]
with the linear extension of the product defined on \( \mathcal{X}^\sigma \) by \( \tau \times \tau' = \sum_{\tau'' \in \mathcal{X}_{|\sigma|+|\tau|+|\tau'|-|\sigma|} p(\tau, \tau', \tau'') \tau'' \).

**Example 2.4.** Here are a few examples to illustrate the notions we just introduced. Letting \( \sigma \) be the unique \( \mathcal{Z} \)-chirotope with \( |\mathcal{Z}| = 2 \), there are exactly seven \( \sigma \)-flags on four points, three with a convex hull of size 4 and four with a convex hull of size 3. The densities of \( \cdot \cdot \cdot \cdot \) into each of these seven \( \sigma \)-flags

\[
\left( \frac{6}{25} \cdots - \frac{11}{125} \cdots \right)^2 + \frac{298819}{1093750} \sum_{\omega \in \mathcal{O}_8} \omega = \sum_{\omega \in \mathcal{O}_8} a_\omega \omega,
\]
where \( a_\omega \leq p(\sigma_4, \omega) \) for every \( \omega \in \mathcal{O}_8 \). This implies that \( p(\sigma_4) \geq 298819/1093750 > 0.2732 \) for any limit of order types \( \ell \). The search for interesting combinations of such inequalities can be done by semidefinite programming.
with 4 points indicated below.

\[
\begin{align*}
p\left( 1^* \cdot 2, 1^* \cdot 2 \right) &= 1, & p\left( 1^* \cdot 2, 2^* \cdot 1 \right) &= 0, \\
p\left( 1^* \cdot 2, 1^* \cdot 2 \right) &= \frac{1}{2}, & p\left( 1^* \cdot 2, 1^* \cdot 2 \right) &= \frac{1}{2}, \\
p\left( 1^* \cdot 2, 1^* \cdot 2 \right) &= 1, & p\left( 1^* \cdot 2, 2^* \cdot 1 \right) &= 0, \\
p\left( 1^* \cdot 2, 1^* \cdot 2 \right) &= \frac{1}{2}.
\end{align*}
\]

Considering the quotient algebra, one sees that

\[
1^* \cdot 1 = 1^* \cdot 1 + 1^* \cdot 1,
\]

and

\[
1^* \cdot 1 = \frac{1}{2} \cdot 1 + \frac{1}{2} \cdot 1.
\]

**Rooted homomorphisms and averaging.** The interest of using the algebras \(\mathcal{A}^\sigma\) to study \(\mathcal{A}\) relies on three tools which we now introduce. We first define an embedding of a \(Z\)-chirotope in an order type \(\omega\) to be a \(\sigma\)-flag with root \(\sigma\) and unlabelling \(\omega\). We use random embeddings with the following distribution in mind: Fix some point set realizing \(\omega\), consider the set \(I\) of injections \(f: Z \rightarrow P\) such that \((P, Z, f)\) is a \(\sigma\)-flag, assume that \(I \neq \emptyset\), choose some injection \(f_r\) from \(I\) uniformly at random, and consider the flag of \((P, Z, f_r)\). We call this the labelling distribution on the embeddings of \(\sigma\) in \(\omega\).

Next, we associate to any convergent sequence of order types \((\omega_n)_{n \in \mathbb{N}}\) with limit \(\ell\), and for every \(Z\)-chirotope \(\sigma\) such that \(\ell(\sigma^\sigma) > 0\), a probability distribution on \(\text{Hom}^+(\mathcal{A}^\sigma, \mathbb{R})\). For every \(n \in \mathbb{N}\), the labelling distribution on embeddings of \(\sigma\) in \(\omega_n\) defines a probability distribution \(P_n^\sigma\) on mappings from \(\mathcal{A}^\sigma\) to \(\mathbb{R}\); specifically, for each embedding \(\theta_n\) of \(\sigma\) in \(\omega_n\) we consider the map \(\ell(\sigma^\sigma) > 0\), the homomorphism induced by \(\ell\) determines the probability distribution \(P_n^\sigma\) [30, Theorem 3.5].

We finally define, for every \(Z\)-chirotope \(\sigma\), an averaging (or downward) operator \(\widehat{\tau}_\sigma: \mathcal{A}^\sigma \rightarrow \mathcal{A}\) as the linear operator defined on the elements of \(\tau \in \mathcal{A}^\sigma\) by \(\tau(\tau)_\sigma = p_{\tau^\sigma}\cdot \tau^\sigma\), where \(p_{\tau^\sigma}\) is the probability that a random embedding of \(\sigma\) to \(\tau^\sigma\) (for the labelling distribution) equals \(\tau\).

**Example 2.5.** Here are a few examples of \(\sigma\)-flags, where \(\sigma = 123\) is the CCW chirotope of size 3:

\[
\begin{align*}
\begin{bmatrix}
1^* & \cdot & 2
\end{bmatrix}_{123} &= \frac{1}{2}, \\
\begin{bmatrix}
1^* & \cdot & 2
\end{bmatrix}_{123} &= \frac{1}{2}, \\
\begin{bmatrix}
1^* & \cdot & 2
\end{bmatrix}_{123} &= \frac{1}{5}.
\end{align*}
\]

For every \(Z\)-chirotope \(\sigma\) and every limit of order types \(\ell\), we have the following important identity [30, Lemma 3.11]:

\[
\forall \tau \in \mathcal{A}^\sigma, \quad \ell\left(\left[\tau\right]_\sigma\right) = \ell\left(\left[\tau\sigma\right]_\sigma\right) \int_{P(\mathcal{A}^\sigma, \mathbb{R})} \phi^\sigma(\tau) \, dP^\sigma_{\ell},
\]

which represents the fact that one can sample \(\left[\tau\right]_\sigma\) by first picking a copy of \(\sigma\) at random, and then, conditioning on the choice of \(\sigma\), extend it to a copy of \(\tau\). Equation (8) in particular implies that \(\ell\left(\left[C^\sigma\sigma\right]_\sigma\right) \geq 0\) for any \(C^\sigma \in \mathcal{A}^\sigma\) such that \(\phi^\sigma(\sigma^\sigma) \geq 0\) almost surely for \(\phi^\sigma \in \text{Hom}^+(\mathcal{A}^\sigma, \mathbb{R})\), relatively to \(P^\sigma_{\ell}\). It follows that for every limit of order types \(\ell\) and every \(Z\)-chirotope \(\sigma\),

\[
\forall C^\sigma \in \mathcal{A}^\sigma, \quad \ell\left(\left(C^\sigma\sigma\right)\right) \geq 0.
\]
2.3 The semidefinite method for order types

The operator $[\cdot]_\sigma$ is linear, so for every $\phi \in \text{Hom}^+(A, R)$, every $A_1^\sigma, A_2^\sigma, \ldots, A_l^\sigma \in A^\sigma$, and every non-negative reals $z_1, z_2, \ldots, z_l$, we have

$$\phi \left( \left[ \sum_{i=1}^l z_i \cdot (A_i^\sigma)^2 \right]_\sigma \right) \geq 0.$$ 

Every real (symmetric) positive semidefinite matrix $M$ of size $n \times n$ can be written as $\sum_{i=1}^n \lambda_i u_i^T u_i$, where $\lambda_1, \ldots, \lambda_n$ are non-negative real numbers and $u_1, \ldots, u_n$ orthonormal vectors of $R^n$. It follows that for every finite set of flags $\mathcal{S} \subseteq \mathcal{O}^n$ and for every real (symmetric) positive semidefinite matrix $M$ of size $|\mathcal{S}| \times |\mathcal{S}|$, we have $\phi \left( \left[ v^T S v \right]_\sigma \right) \geq 0$, where $v_S$ is the vector in $(A^\sigma)^{|\mathcal{S}|}$ whose $i$th coordinate equals the $i$th element of $\mathcal{S}$ (for some given order). This recasts the search for a good “positive” quadratic combination as a semidefinite programming problem.

Let $N$ be an integer, $f = \sum_{\omega \in \mathcal{O}_N} f_\omega$ some target function, and $\sigma_1, \ldots, \sigma_k$ a finite list of chirotopes so that $|\sigma_i| \equiv N \mod 2$. For each $i \in [k]$, let $v_i$ be the $|X_{(N+|\sigma_i|)/2}^\sigma|$-dimensional vector with $i$th coordinate equal to the $i$th element of $X_{(N+|\sigma_i|)/2}^\sigma$. We look for a real $b$ as large as possible subject to the constraint that there are $k$ real (symmetric) positive semidefinite matrices $M_1, M_2, \ldots, M_k$, where $M_i$ has size $|v_i| \times |v_i|$, so that

$$\forall \omega \in \mathcal{O}_N, \quad f_\omega \geq a_\omega \quad \text{where} \quad \sum_{\omega \in \mathcal{O}_N} a_\omega \omega = \sum_{i \in [k]} \left[ u_i^T M_i v_i \right]_{\sigma_i} + b \sum_{\omega \in \mathcal{O}_N} \omega. \quad (10)$$

The values of the real numbers $a_\omega$ are determined by $b$, the entries of the matrices $M_1, M_2, \ldots, M_k$, the splitting probabilities $p(\tau', \tau''; \tau)$, where $\tau', \tau'' \in X_{(N+|\sigma_i|)/2}^\sigma$, and $\tau \in X_{N}^\sigma$, and the probabilities $p_{\tau_i}^\sigma$, where $\tau \in \mathcal{O}_N^\sigma$. Moreover, finding the maximum value of $b$ and the entries of the matrices $M_i$ can be formulated as a semidefinite program.

Effective semidefinite programming for flags of order types. In order to use a semidefinite programming software for finding a solution of programs in the form of (10), it is enough to generate the sets $\mathcal{O}_N$ and $X_{N}^\sigma$, the split probabilities $p(\tau', \tau''; \tau)$, where $\tau', \tau'' \in X_{(N+|\sigma_i|)/2}^\sigma$ and $\tau \in X_{N}^\sigma$, and the probabilities $p_{\tau_i}^\sigma$, where $\tau \in \mathcal{O}_N^\sigma$.

We generated the sets and the values by brute force up to $N = 8$. The only non-trivial algorithmic step is deciding whether two order types, represented by point sets, are equal. This can be done by computing some canonical ordering of the points that turn two point sets with the same order type into point sequences with the same chirotope. A solution taking $O(n^2)$ time was proposed by Aloupis et al. [7]; the method that we implemented takes time $O(n^2 \log n)$ and seems to be folklore (we learned it from Pocchiola and Pilaud). For solving the semidefinite program itself, we used a library called CSDP [10]. The input data for CSDP was generated using the mathematical software SAGE [35].

Setting up the semidefinite programs. In the rest of this section we work with $N = 8$ and use chirotopes labelled $\sigma_1, \sigma_2, \ldots, \sigma_{24}$ with $\sigma_1$ being the empty chirotope, $\sigma_2$ the only chirotope of size two, $\sigma_3$ and $\sigma_4$ the two chirotopes of size 4 depicted on the left, and $\sigma_5, \ldots, \sigma_{24}$ a fixed set of 20 chirotopes of size 6 so that $\mathcal{O}_6 = \{\sigma_5^6, \ldots, \sigma_{24}^6\}$. Note that since $|\mathcal{O}_6| = 20$, what follows does not depend on the choices made in labelling $\sigma_5, \ldots, \sigma_{24}$. The vectors $v_1, \ldots, v_{24}$ described in the previous paragraph for this choice of $N$ and $\sigma_i$’s have respective lengths 2, 44, 468, 393, 122, 112, 114, 101, 103, 106, 103, 103, 120, 102, 108, 94, 90, 91, 91, 95, 95, 92 and 104.

Computations proving Proposition 1 and Proposition 2. We solved two semidefinite programs with the above choice of parameters for $f = \sum_{\omega \in \mathcal{O}_8} p(\sigma_5, \omega)$ and $f = \sum_{\omega \in \mathcal{O}_8} p(\sigma_6, \omega)$ and obtained real symmetric positive semidefinite matrices $M_1, \ldots, M_{24}$ and $M_1', \ldots, M_{24}'$ with rational entries so that

$$\sum_{\omega \in \mathcal{O}_8} p(\sigma_5, \omega) \omega \geq \sum_{i \in [24]} \left[ u_i^T M_i v_i \right]_{\sigma_i} + \frac{15715211616602583691}{25825441703193372264} \sum_{\omega \in \mathcal{O}_8} \omega,$$
and
\[ \sum_{\omega \in \mathcal{O}_6} p(\omega, \omega) \omega \geq \sum_{i \in [24]} [v_i^T M_i v_i]_{\sigma_i} + \frac{67557324685725989}{36893488147419103232} \sum_{\omega \in \mathcal{O}_6} \omega. \]

The lower bounds on \( c_3 \) and \( c_4 \) then follow from Equation (2).

Assume (without loss of generality) that \( \mathcal{O}_6 = \{ \omega_{6,1}, \omega_{6,2}, \ldots, \omega_{6,20} \} \). Solving two semidefinite programs, we obtained real symmetric positive semidefinite matrices \( M_1, \ldots, M_{24} \) and \( M'_1, \ldots, M'_{24} \) as well as non-negative rational values \( d_1, \ldots, d_{20} \) and \( d'_1, \ldots, d'_{20} \) so that
\[
\sum_{j \in [20]} d_j \left( \omega_{6,j} - \frac{1}{32} \sum_{\omega \in \mathcal{O}_6} \omega \right) + \sum_{i \in [24]} [v_i^T M_i v_i]_{\sigma_i} < 0
\]
and
\[
\sum_{j \in [20]} d'_j \left( -\omega_{6,j} + \frac{1}{18} \sum_{\omega \in \mathcal{O}_6} \omega \right) + \sum_{i \in [24]} [v_i^T M_i v_i]_{\sigma_i} < 0.
\]

They respectively imply that there is no \( \ell \in \text{Hom}^+(A, \mathbb{R}) \) such that, \( \ell(\omega) \geq 1/32 \) for every \( \omega \in \mathcal{O}_6 \), or such that \( \ell(\omega) \leq 1/18 \) for every \( \omega \in \mathcal{O}_6 \). Altogether this proves Proposition 2 with an imbalance bound of 32/18 > 1.77. The better bound of Proposition 2 is obtained by a refinement of this approach where the order types with minimum and maximum probability are prescribed; this requires solving over 700 semidefinite programs.

The numerical values of the entries of all the matrices \( M_1, \ldots, M_{24} \) and coefficients \( d_1, \ldots, d_{20} \) mentioned above can be downloaded from the web page \texttt{http://honza.ucw.cz/proj/ordertypes/}. In fact, the matrices \( M_1, \ldots, M_{24} \) are not stored directly, but as an appropriate non-negative sum of squares, which makes the verification of positive semidefiniteness trivial. To make an independent verification of our computations easier, we created sage scripts called \texttt{verify_prop.sage}, available from the same web page.

3 Representation of limits by measures

Corollary 8 asserts that every probability (or finite Borel measure) over \( \mathbb{R}^2 \) that charges no line defines a limit of order types. Going in the other direction, we say that a measure \( \mu \) realizes a limit of order types \( \ell \) if \( \ell(\mu) = \ell \). We examine here two questions: does every limit of order types enjoy such a realization and, for those that do, what does the set of measures realizing them look like? We answer the first question negatively in Section 3.2. We then give partial answers to the second question in Section 3.3 and Section 3.4. Every measure of \( \mathbb{R}^2 \) or on \( S^2 \) that we consider is defined on the Borel \( \sigma \)-algebra.

3.1 Spherical geometry

If \( \mu \) is a measure that charges no line and \( f: \text{supp} \mu \rightarrow \mathbb{R}^2 \) is an injective map that preserves orientations, then \( \mu' = \mu \circ f^{-1} \) is another measure that realizes the same limit as \( \mu \). A map that preserves orientations must preserve alignments, and therefore coincides locally with a projective map. Note, however, that if we fix two points \( p, q \in \mathbb{R}^2 \) and take a third point \( r \) “to infinity” in directions \( \pm \tilde{u} \), the orientation of the triple \((p, q, r)\) is different for \(+\tilde{u}\) and for \(-\tilde{u}\). The appropriate geometric setting is therefore not projective, but spherical.

The spherical model. For convenience, we write \( \{ z > 0 \} \) for \( \{ (x, y, z) \in \mathbb{R}^3 \mid z > 0 \} \) and, similarly, \( \{ z < 0 \} \) and \( \{ z = 0 \} \) stand for \( \{ (x, y, z) \in \mathbb{R}^3 \mid z < 0 \} \) and for \( \{ (x, y, z) \in \mathbb{R}^3 \mid z = 0 \} \), respectively. Consider the standard identification of \( \mathbb{R}^2 \) with the open upper half of the unit sphere in \( \mathbb{R}^3 \) given by the bijection:

\[
\iota: \begin{cases} 
\mathbb{R}^2 & \rightarrow \mathbb{S}^2 \cap \{ z > 0 \} \\
(x, y) & \mapsto \frac{1}{\sqrt{x^2+y^2+1}} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}.
\end{cases}
\]
The map \( \iota \) sends the lines of \( \mathbb{R}^2 \) to the intersection of the half-space \( z > 0 \) with the great circles of \( \mathbb{S}^2 \), that is circles cut out by planes through the center of that sphere, other than the circle contained in the plane \( z = 0 \). We can define the orientation of a triple \((p, q, r)\) of points of \( \mathbb{S}^2 \) as the sign of \( \det(p, q, r) \), so that it coincides, through \( \iota \), with the planar notion. Naturally, \( \iota \) transports planar measures that charge no line into spherical measures, supported on \( \mathbb{S}^2 \cap \{ z > 0 \} \), that charge no great circle.

**Spherical transforms.** Let \( X, Y \subset \mathbb{R}^2 \). A function \( f: X \to Y \) is a spherical transform if there exist a direct affine transform \( g \) and a rotation \( h \in \text{SO}(\mathbb{R}^3) \) such that \( h(\iota(X)) \subseteq \{ z > 0 \} \) and \( f = (g \circ \iota^{-1} \circ h \circ \iota)|_X \). In words, spherical transforms are compositions of direct affine transforms with a lifting of \( \mathbb{R}^2 \) to the upper half of \( \mathbb{S}^2 \), a rotation that keeps the image of the lifting within that upper half-sphere, then a backprojection from that upper sphere to \( \mathbb{R}^2 \). Notice that \( f \) is defined over all of \( \mathbb{R}^2 \) if \( h \) preserves the great circle \( \mathbb{S}^2 \cap \{ z = 0 \} \), and on the open halfplane \( \iota^{-1}(\{ z > 0 \} \cap h^{-1}(\{ z > 0 \})) \) otherwise.

**Lemma 3.1.** If \( \mu \) is a measure in \( \mathbb{R}^2 \) that charges no line and \( f \) is a spherical transform defined over \( \text{supp} \mu \), then \( \ell_{\mu} = \ell_{\mu \circ f^{-1}} \).

*Proof. The statement follows from the observation that \( f \) preserves orientations over \( \text{supp} \mu \). To see this, let \( p, q, r \in \text{supp} \mu \) and let us decompose \( f = (g \circ \iota^{-1} \circ h \circ \iota)|_{\text{supp} \mu} \) where \( g \) is a direct affine transform and \( h \in \text{SO}(\mathbb{R}^3) \). Translations preserve orientation. Writing orientations as determinants reveals that direct linear transforms also preserve orientations. Altogether, the direct affine transform \( g \) thus also preserves orientations. It follows that

\[
[f(p), f(q), f(r)] = [g \circ \iota^{-1} \circ h \circ \iota(p), g \circ \iota^{-1} \circ h \circ \iota(q), g \circ \iota^{-1} \circ h \circ \iota(r)]
\]

\[
= [-1 \circ h \circ \iota(p), \iota^{-1} \circ h \circ \iota(q), \iota^{-1} \circ h \circ \iota(r)]
\]

\[
= \text{sign} \det(h \circ \iota(p) \circ \iota(q) \circ \iota(r))
\]

\[
= \text{sign} \left( \det(h) \det(\iota(p) \circ \iota(q) \circ \iota(r)) \right)
\]

\[
= \text{sign} \left( \det(h) \right) [p, q, r],
\]

and \( f \) preserves orientations because \( h \) is direct. \qed

**Lemma 3.2.** Let \( C \) be a closed convex set and \( L \) a line in \( \mathbb{R}^2 \). If \( d(C, L) > 0 \) and \( C \) contains no ray parallel to \( L \), then there exists a spherical transform \( f \) defined over \( C \) such that \( f(C) \) is compact.

*Proof. Let \( X \) be the open halfplane bounded by \( L \) that contains \( C \). The image \( \iota(L) \) coincides with the intersection of a great circle \( \Gamma \) with \( \{ z > 0 \} \). Moreover, \( \iota(X) \) is contained in one of the hemispheres bounded by \( \Gamma \). Let \( h \in \text{SO}(\mathbb{R}^3) \) be a rotation that maps \( \Gamma \) to \( \mathbb{S}^2 \cap \{ z = 0 \} \) and maps the interior of \( \iota(X) \) to (a subset of) the region \( \{ z > 0 \} \). We set \( f = (\iota^{-1} \circ h \circ \iota)|_X \).

We argue that if \( f(C) \) is unbounded, then \( d(C, L) = 0 \) or \( C \) contains a ray parallel to \( L \). Let \( (p_n)_{n \in \mathbb{N}} \subset C \) such that \( \{ f(p_n) \}_{n \in \mathbb{N}} \) is unbounded. Since \( \mathbb{S}^2 \) is compact, up to taking a subsequence we can assume that \( \{ h \circ \iota(p_n) \} \) converges. Its limit \( u \) must belong to \( \{ z = 0 \} \), as otherwise \( \iota^{-1}(u) \in \mathbb{R}^2 \), which would contradict the assumption that \( \{ f(p_n) \} \) is unbounded. This means that \( \{ \iota(p_n) \} \) converges to a limit \( u' = h^{-1}(u) \in \Gamma \). If \( u' \notin \iota(L) \), then \( d(C, L) = 0 \). If \( u' \in \iota(L) \), then \( u' \in \Gamma \cap \{ z = 0 \} \) and we can write \( u' = (u_x : u_y : 0) \) where \( \tilde{u}' = (u_x, u_y) \) is a unit direction vector for \( L \) to which the vectors \( \left( \frac{p_1}{\| p_1 \|}, \frac{p_2}{\| p_2 \|}, \ldots \right)_{n \in \mathbb{N}} \) converge. For any positive real number \( t > 0 \) and for any large enough integer \( n \) we have \( \| p_1 q_n \| > t \), so the segment \( p_1 q_n \) contains a point \( q \) with \( \| p_1 q_n \| = t \). The sequence \( \{ q_n \} \) is contained in \( C \) by convexity, and converges to \( p_1 + tu \). Since \( C \) is closed, this limit is also in \( C \). The ray \( p_1 + R^+u \) is thus in \( C \), which contradicts the assumption that \( C \) contains no ray parallel to \( L \). We deduce that \( f(C) \) is bounded and thus, altogether, the assumptions on \( L \) and \( C \) guarantee that \( f(C) \) is compact. \qed

**3.2 A limit that is not representable**

For convenience, let us repeat the definition of \( \ell_{\delta_0} \) from the introduction. For \( t \in (0,1) \) let \( \varphi_t \) be the probability distribution over \( \mathbb{R}^2 \) supported on two concentric circles, with respective radii 1 and \( t \) where
each of the two circles has $\odot$-measure 1/2, distributed proportionally to the length on that circle. We define $\ell_\odot$ to be the limit of order types associated to $\odot$. We define $\ell_\odot$ to be the limit of an arbitrary convergent sub-sequence of $(\ell_{\odot/n})_{n \in \mathbb{N}}$.

We use the following two facts about measures, limits of order types, and sequences of point sets. Let $\mu$ be a measure of the plane, and $P_n$ a set of $n$ points of the plane sampled i.i.d. according to $\mu$. The empirical measure associated to $P_n$ is the measure $\mu_{P_n}$ defined on all $\mu$-measurable subsets $A$ of $\mathbb{R}^2$ by

$$\mu_{P_n}(A) = \frac{1}{n}|P_n \cap A|.$$ 

Lemma 3.3. Let $\mu$ be a measure that does not charge lines and for $n \geq 1$, let $P_n$ be a set of points sampled independently from $\mu$, with $|P_n| \to \infty$. The empirical measure of $P_n$ almost-surely weakly converges to $\mu$.

The next lemma follows from ideas similar to those used in the proof of Proposition 7.

Lemma 3.4. Let $\mu$ be a measure that does not charge lines. If $(P_n)_{n \in \mathbb{N}}$ is a sequence of point sets with $|P_n| = n^2$ and whose empirical measures converge to $\mu$ as $n$ goes to infinity, then the order type of $P_n$ converges to $\ell_\mu$ as $n$ goes to infinity.

3.2.1 Reduction to compact support

Define the peeling depth of an order type $\omega$ as the largest integer $k$ such that $P_k \neq \emptyset$ in a sequence $\{P_i\}_{i \in \mathbb{N}}$ where $P_i$ realizes $\omega$ and $P_{i+1} = P_i \setminus \text{conv}(P_i)$ for each $i \geq 1$. For instance, $k$ points in convex position have peeling depth 1, and any $k$ points chosen from the support of $\odot$ have peeling depth at most 2.

Lemma 3.5. Fix $k \in \mathbb{N}$ and let $\ell$ be a limit of order types such that $\ell(\omega) = 0$ for any order type $\omega$ of peeling depth greater than $k$. If there exists a probability measure $\mu$ realizing $\ell$, then there exists one with compact support.

Proof. Let $\mu$ be a probability measure that realizes $\ell$ and let $C = \text{conv sup} \mu$. If an order type $\omega$ can be realized by points in the support of $\mu$, then $\ell_\mu(\omega) > 0$. Indeed, for a positive and sufficiently small $\varepsilon$, any perturbation of the points of amplitude at most $\varepsilon$ also realizes $\omega$. It follows that the support of $\mu$ cannot contain any finite subset with peeling depth $k+1$.

We first argue that $C \neq \mathbb{R}^2$. We proceed by contradiction, so suppose $C = \mathbb{R}^2$. A theorem of Steinlitz [36] asserts that for any subset $A \subseteq \mathbb{R}^2$, any point in the interior of $\text{conv} A$ belongs to the interior of the convex hull of at most four points of $A$. For any point $p \in \mathbb{R}^2$, there is thus a quadruple $Q(p) \subseteq \text{supp} \mu$ such that $p$ belongs to the interior of $\text{conv} Q(p)$. We now define $Y_1 = \{p_1\}$ where $p_1$ is an arbitrary point of $\text{supp} \mu$, and $Y_{i+1} = \bigcup_{p \in Y_i} Q(p)$ for each $i \geq 1$. The set $\bigcup_{i=1}^{\infty} Y_i$ is contained in the support of $\mu$ and has peeling depth at least $k+1$, a contradiction. Consequently, $C$ cannot be $\mathbb{R}^2$.

We can also rule out the case where $C$ is a halfplane. Suppose the contrary and let $L$ be the line bounding this halfplane. We can follow the argument showing that $C \neq \mathbb{R}^2$, except if at some stage, some point of $Y_i$ belongs to $L$. Assume that this is the case for $p \in Y_i$, and note that we can assume that $i \geq 2$. There exists $p' \in Y_{i-1}$ such that $p \in Q(p')$; remark that the peeling depth of $\bigcup_{j=i}^{\infty} Y_j$ remains at least $i$ if we replace $p$ in $Y_i$ by any point $q$ in $\text{supp} \mu$ such that $p'$ belongs to the interior of $\text{conv} Q(p') \setminus \{p\} \cup \{q\}$. There exists $\varepsilon_1 > 0$ such that for any $z \in B(p, \varepsilon_1)$, the point $p'$ belongs to the interior of $\text{conv} Q(p') \setminus \{p\} \cup \{z\}$. Let $\tau = \mu(B(p, \varepsilon_1))$. Since $\mu(L) = 0$, there exists $\delta > 0$ such that the set of points within distance $\delta$ of $L$ has measure at most $\varepsilon_1/2$. The part of $B(p, \varepsilon_1)$ at distance at least $\delta$ from $L$ therefore has measure at least $\varepsilon_1/2$. A dichotomy argument produces a point $q$ in that part that is in the support of $\mu$. We can replace $p$ by $q$ in $Y_i$ and continue with the construction. It follows that $C$ cannot be a halfplane.

For any point $p \in \partial C$ there is a line supporting $C$ and containing $p$. Thus, since $C$ is neither $\mathbb{R}^2$ nor a halfplane, $C$ is contained in the intersection of two non-parallel, closed, halfplanes $H_1$ and $H_2$. Let $L$ be a line disjoint from $H_1 \cap H_2$ that is parallel to neither $\partial H_1$ nor $\partial H_2$. Note that Lemma 3.2 applies, so there is a spherical transform $f$ defined over $\text{supp} \mu$. Lemma 3.1 ensures that the pushback of $\mu$ by $f$ is a measure with compact support that defines the same limit of order types as $\mu$.

Corollary 10. If $\ell_\odot$ is realizable by a measure, then it is realizable by one with compact support.
Proof. For any \( t \in (0, 1) \), if an order type \( \omega \) has peeling depth at least 3, then \( \ell_{\circ}(\omega) = 0 \). It follows that \( \ell_{\circ} \) vanishes on every order type of peeling depth three or more and therefore Lemma 3.5 yields the conclusion. \( \Box \)

3.2.2 Excluding realizations with compact support

Assume by contradiction that there exists a measure \( \mu \) that realizes \( \ell_{\circ} \); in particular, \( \mu \) charges no line. Let \( P_n \) be a set of \( N = n^2 \) random points sampled independently from \( \mu \). By Lemma 3.3, the empirical measures of \( \{P_n\}_n \) weakly converge to \( \mu \) and by Lemma 3.4, their order types converge to \( \ell \). We write \( C_n = P_n \cap \partial \text{conv } P_n \) for the extreme points of \( P_n \) and \( I_n = P_n \setminus C_n \) for the remaining points.

**Lemma 3.6.** With high probability, \( 0.49 N \leq |C_n| \leq 0.51 N \) and at least \( f(N) \) edges of \( \text{conv } P_n \) form, with another vertex of \( C_n \), a triangle that contains \( I_n \), where \( \lim_{N \rightarrow \infty} f(N) = +\infty \).

Before we prove Lemma 3.6, let us see how to use it by establishing Proposition 3.

**Proof of Proposition 3.** Suppose, contrary to the statement, that there exists a measure \( \mu \) that realizes \( \ell_{\circ} \). In particular, \( \mu \) charges no line. By Corollary 10, we can assume \( \mu \) to have compact support. Let \( \alpha \) be the length of the boundary of \( \text{conv } P_n \). Note that \( \alpha < \infty \) since \( \mu \) has compact support. Since \( \text{conv } P_n \) is contained in \( \text{conv } supp \mu \), the boundary of \( \text{conv } P_n \) also has length at most \( \alpha \) (this follows for instance from the Cauchy-Crofton formula [31, Chapter 3, §2]). Lemma 3.6 implies that there is an edge of \( \text{conv } P_n \) of length at most \( \varepsilon = O \left( \frac{\alpha}{\sqrt{N}} \right) \) that forms, together with another vertex of \( C_n \), a triangle containing \( I_n \). Let \( L_n \) be the line supporting one of the edges of this triangle that is not on \( \partial \text{conv } P_n \). With high probability, at least \( 0.49 |P_n| \) points of \( P_n \) lie within distance at most \( \varepsilon \) of \( L_n \). The set of lines intersecting \( \text{conv } supp \mu \) is compact, so the sequence \( (L_n)_n \) contains a subsequence \( (L_{n(i)})_i \) converging to a line \( L \). Since the empirical measures of \( (P_{n(i)})_i \) converge to \( \mu \), we deduce that \( \mu(L) \geq 0.49 \), a contradiction. \( \Box \)

It remains to prove Lemma 3.6.

**Proof of Lemma 3.6.** Let us give another model of random point sets whose order-type is distributed like \( P_n \). Let \( \mathcal{C}_t \) be the circle of radius \( t \) in \( \mathbb{R}^2 \) centered at the origin. We let \( P_n^{1/2} \) be a set of \( N = n^2 \) random points sampled independently from \( \mathbb{S}_{1/2} \) and for \( t \in (0, \frac{1}{2}) \) we let \( P_n^t \) be the point set obtained from \( P_n^{1/2} \) by scaling the points on \( \mathbb{S}_{1/2} \) from the origin by a factor \( 2t \). Observe that \( P_n^t \) is distributed like \( N \) points sampled independently from \( \mathbb{S}_t \). Moreover, almost surely, there exists (a random variable) \( t^* > 0 \) such that the order types of \( P_n^t \) are identical for \( t \in (0, t^*) \). As \( t \to 0 \), the sequence \( (\ell_{\circ t})_t \) converges to \( \ell_{\circ} = \ell_{\mu} \), so the order type of \( P_n^{t^*} \) is distributed like \( P_n \).

Let us define \( C_n^{t^*} = P_n^{t^*} \cap \partial \text{conv } P_n^{t^*} \) and \( I_n^{t^*} = P_n^{t^*} \setminus C_n^{t^*} \). We assert that with high probability

(a) \( 0.49 N \leq |P_n^{t^*} \cap \mathcal{C}_1| \leq 0.51 N \); and

(b) \( C_n^{t^*} = P_n^{t^*} \cap \mathcal{C}_1 \).

Since the order types of \( P_n \) and \( P_n^{t^*} \) are identically distributed, this claim implies in particular the first part of the statement.

Assertion (a) follows from Hoeffding’s inequality because the repartition of the points of \( P_n^{t^*} \) between \( \mathcal{C}_1 \) and \( \mathcal{C}_{t^*} \) follows a binomial law with parameter 1/2. To prove Assertion (b), let us bound the probability that there exists a point from \( \mathcal{C}_{t^*} \) on \( \partial \text{conv } P_n^{t^*} \). If such a point exists, then there is a line through that point that cuts an arc of \( \mathcal{C}_1 \) with no point of \( P_n^{t^*} \). Any line through a point of \( \mathcal{C}_{t^*} \) cuts an arc of \( \mathcal{C}_1 \) with length at least a fraction \( \alpha(t^*) \) of the length of \( \mathcal{C}_1 \). We can now cover \( \mathcal{C}_1 \) by smaller intervals of length \( \alpha(t^*)/2 \), and we observe that \( P_n^{t^*} \) must miss at least one of these smaller intervals. For \( t^* \) small enough, 8 smaller intervals suffice, and \( C_n^{t^*} = P_n^{t^*} \cap \mathcal{C}_1 \) with probability least \( 1 - 8 \left( \frac{1}{16} \right)^N \). This proves our assertion.

Let us now turn our attention to the second part of the statement of the lemma. We write \( C_n^{t^*} = \{p_1, p_2, \ldots \} \) where the points are labelled in clockwise order along \( \partial \text{conv } P_n^{t^*} \), starting in an arbitrary place. We label the points cyclically, setting \( p_{i + |C_n^{t^*}|} = p_i \). Almost surely, for every \( i \) the antipodal of \( p_i \)
is not in \( C_n^T \) so there exists a unique edge \( p_ip_{i+1} \) such that \( p_ip_{j+1} \) contains \( T_n^T \). We set \( j(i) = j \). Our task is to bound from below the number of distinct edges \( p_ip_{j(i)}p_{j(i)+1} \).

Let us associate to every point \( p_i \) the random variables \( s_i = |i - j(i)| \). We assert that with high probability

\[
\frac{|C_n^T|}{2} - N^{-\frac{2}{3}} \leq \min_i s_i \leq \max_i s_i \leq \frac{|C_n^T|}{2} + N^{-\frac{2}{3}}. \tag{11}
\]

Observe that (11) implies that \( j(i) \) is different for any two indices \( i \in \{0, 1, 2, 3, \ldots, \), \( k + 0.1)N^{2/3} \) where \( k \in \mathbb{N} \) such that \( (k + 0.1)N^{2/3} \leq 0.49N < (k + 1.1)N^{2/3} \). It follows that with high probability \( j(i) \) takes at least \( \Omega(N^{1/3}) \) different values, proving the second statement.

It remains to establish (11). The random variable \( s_i \) counts the number of points on one of the halfcircles of \( C_1 \) bounded by \( p_i \) and its antipodal. Consider a different labeling \( C_n^T = \{q_1, q_2, \ldots \} \) where \( q_1 \) is an arbitrary point of \( C_n^T \) and where the lines through the origin and \( q_1, q_2, \ldots \) are in clockwise order. Each \( s_i \) counts the number of \( q_j \neq p_i \) on the clockwise half-circle from \( p_i \) to its antipodal. Observe that the position of the lines spanned by the points \( q_i \) and their antipodals are irrelevant; in fact, fixing the lines arbitrarily and picking each \( q_i \) uniformly among the two candidate points on its assigned line leads to the same distribution of the variables \( s_i \). A purely combinatorial, equivalent, description is thus the following. Let \( W = w_1w_2 \ldots w_{2k} \) be a random circular word on \( \{0, 1\}^{2k} \), where \( k = |C_n^T|, w_{i+k} = 1 - w_i \) and the letters \( w_1, w_2, \ldots, w_k \) are chosen independently and uniformly in \( \{0, 1\} \). The random variable \( s_i \) has the same distribution as \( w_i + w_{i+1} + \cdots + w_{i+k-1} \). Hoeffding’s inequality and a union bound then yield that with high probability, \( \max_i s_i \) is at most \( \frac{3}{2} + o(k) \) (and, by symmetry, that \( \min_i s_i \) is at least \( \frac{3}{2} - o(k) \)).

3.3 The rigidity theorem

In this section, we prove Theorem 4, which states that probability distributions giving rise to the same limit of order types are projectively equivalent, provided that their support have non-empty interiors.

We proceed by adapting the notion of kernels to three-variable functions. This notion generalizes the notion of geometric limit firstly by allowing probability measures of any topological space \( J \) instead of probability measures on \( \mathbb{R}^2 \) and secondly by using any real-valued function of \( J^3 \) instead of the chirotope of the plane. Our main tool\(^2\) on kernels is Theorem 13, which asserts that two kernels have same sampling distribution if and only if they are isomorphic. We introduce the notions related to kernels and state Theorem 13 in Section 3.3.1, but defer all proofs to Section 3.3.3, after we have examined kernels defined from geometric probabilities and order types and deduced Theorem 4 (Section 3.3.2).

3.3.1 Rigidity for kernels (overview)

A kernel is a triple \((J, \mu, W)\) where \((J, \mu)\) is a probability space and \(W\) is a measurable map from \(J^3\) to \(\mathbb{R}\) such that \(\sup_{j} |W| < \infty\). For the sake of readability, \(W\) can stand for a whole kernel \((J, \mu, W)\) when there is no ambiguity about the set and the measure involved. We are, in particular, interested in kernels based on chirotopes, that is, where \(J = \mathbb{R}^2, \mu\) is a measure that charges no line, and \(W\) is a map to \(\{-1, 0, 1\}\) given by the orientation.

Our first ingredient is a rigidity theorem for kernels (Theorem 13), which asserts that if two kernels have the same density functions (the analogue, for general kernels, of the limit of order types \(\ell_\mu\) associated with a measure \(\mu\)), then they are essentially equal. We present here the main notions and results, and postpone the proofs to Section 3.3.3.

Density function. A step function over a probability space \((J, \mu)\) is a kernel \((J, \mu, U)\) for which there is a partition \((P_1, \ldots, P_m)\) of \(J\) such that the function \(U\) is constant on \(P_i \times P_j \times P_k\) for every \((i, j, k) \in [m]^3\). Since the set \(U^{-1}(\{x\})\) is measurable for every \(x \in \mathbb{R}\), we may always assume that \(P_i\) is measurable for \(i \in [m]\).

\(^2\)This result and its proof are direct adaptations of similar results on two-dimensional kernels and graphs; the presentation reaches the proof of Proposition 12 as directly as possible, and we refer to the monograph of Lovász [25] for (a lot) more details on two-dimensional kernels.
Let \( (J, \mu, W) \) be a kernel and \( n \) a positive integer. Any \( n \)-tuple \( S = (x_1, \ldots, x_n) \in J^n \) defines a function
\[
H(W, S): \left\{ \begin{array}{c}
[i,j,k]^3 \to \mathbb{R} \\
(i,j,k) \to W(x_i, x_j, x_k).
\end{array} \right.
\]
We observe that if \( \mu_n^J \) is the counting measure on \([n]\), then \( (\mu_n^J, H(W, S)) \) is a step function for the partition of \([n]\) into singletons. We let \( H(W, n) \) be the random step function \( H(W, S) \), where \( S \) is a \( \mu_n^J \)-random tuple. We define \( \mathcal{H}_n \) to be \( \{ H : [n]^3 \to \mathbb{R} \} \). For every \( H \in \mathcal{H}_n \), the density \( t(H, W) \) of \( H \) in \( W \) is the probability that \( H(W, n) = H \). We set \( \mathcal{H} = \bigcup_{n \geq 1} \mathcal{H}_n \).

**Norms and distance.** A kernel \( (J, \mu, W) \) has associated \( L_1 \)- and \( L_\infty \)-norms respectively defined by
\[
\|W\|_1 = \int_{J^3} |W(x, y, z)| \, d\mu(x) \, d\mu(y) \, d\mu(z) \quad \text{and} \quad \|W\|_\infty = \sup_{j^3} |W|.
\]
The \( L_1 \)- and \( L_\infty \)-norms define distances only between kernels with the same underlying probability space. To define a distance between any two kernels \( (J_1, \mu_1, W_1) \) and \( (J_2, \mu_2, W_2) \), we first map them both to a common probability space by measure-preserving\(^3\) maps (like the Gromov-Hausdorff distance between metric spaces). Specifically, we define
\[
d(W_1, W_2) = \inf \left\| W_1^\phi_1 - W_2^\phi_2 \right\|_1
\]
where the infimum is taken over all choices of a probability space \((J, \mu)\) and a pair of measure-preserving maps \( \phi_i : J \to J_i \) for \( i \in \{1, 2\} \), and where \( W^\phi \) is defined by \( W(x, y, z) = W(\phi(x), \phi(y), \phi(z)) \). This infimum does not change if we assume that \( \mu \) is a coupling measure on \( J = J_1 \times J_2 \) and that \( \phi_i \) is the natural projection of \( J \) on \( J_i \) for \( i \in \{1, 2\} \). Further, a theorem by Janson [21, Theorem 2] ensures that, up to a measure-preserving map, we can also assume that \( J_i \) is \([0, 1]\) and \( \mu_i \) is the Lebesgue measure for \( i \in \{1, 2\} \).

**Rigidity of kernels.** We now turn our attention to rigidity results for kernels. Unless otherwise specified, all topological hypothesis are to be understood in \( \mathbb{R}^2 \) endowed with the usual topology; this is in particular the case when we consider a measure with “non-empty interior”. We start with the following.

**Theorem 11.** If \( (J_1, \mu_1, W_1) \) and \( (J_2, \mu_2, W_2) \) are two kernels such that \( t(H, W_1) = t(H, W_2) \) for every function \( H \in \mathcal{H} \), then \( d(W_1, W_2) = 0 \).

Theorem 11 makes no assumption on the measure, but the equality of \( W_1 \) and \( W_2 \) is only in measure, up to mapping to a common probability space. Stronger rigidity properties are possible under some regularity assumption on the kernels. Define two points \( x, x' \) in \( J \) to be twins for \((J, \mu, W)\) if \( W(x, y, z) = W(x', y, z) \) for \( \mu^2 \)-almost every pair \((y, z) \in J^2\). The kernel \((J, \mu, W)\) is twin-free if it admits no twins.

**Proposition 12.** Let \( (J_1, \mu_1, W_1) \) and \( (J_2, \mu_2, W_2) \) be two twin-free kernels. If \( t(H, W_1) = t(H, W_2) \) for every function \( H \in \mathcal{H} \), then there exist two sets \( N_1 \subseteq J_1 \) and \( N_2 \subseteq J_2 \) with \( \mu_1(N_1) = 0 = \mu_2(N_2) \) and a bijection \( \rho : J_1 \setminus N_1 \to J_2 \setminus N_2 \) such that \( \rho \) and \( \rho^{-1} \) are measure preserving, and \( W_1 \) and \( W_2 \) are equal \( \mu^2 \)-almost everywhere.

For even more regular kernels, there are in fact distances on \( J_1 \) and \( J_2 \) such that a measure-preserving isometry exists. Specifically, the *neighborhood pseudo-distance* of a kernel \((J, \mu, W)\) is the function \( d_W : J \times J \to \mathbb{R}^+ \) given by
\[
\forall (x, x') \in J^2, \quad d_W(x, x') = \|W(x, \cdot, \cdot) - W(x', \cdot, \cdot)\|_1 = \int_{J^2} |W(x, y, z) - W(x', y, z)| \, d\mu(y) \, d\mu(z).
\]
It is straightforward to check that \( d_W \) is reflexive and satisfies the triangular inequality, so it is a distance if and only if it is separated, i.e., if \((J, W, \mu)\) is twin-free.

\(^3\)If \((J_1, \mu_1)\) and \((J_2, \mu_2)\) are two probability spaces, a map \( \rho : J_1 \to J_2 \) is measure preserving if for every \( \mu_2 \)-measurable set \( A' \subseteq J_2 \), the set \( A = \rho^{-1}(A') \) is \( \mu_1 \)-measurable and \( \mu_1(A) = \mu_2(A') \).
A kernel \((J, \mu, W)\) is pure if (i) the map \(d_W\) is a distance on \(J\), (ii) the metric space \((J, d_W)\) is complete and separable, and (iii) the measure \(\mu\) has full support, that is, every non-empty open set of \((J, d_W)\) has positive \(\mu\)-measure.

**Theorem 13.** Let \((J_1, \mu_1, W_1)\) and \((J_2, \mu_2, W_2)\) be two pure kernels. If \(t(H, W_1) = t(H, W_2)\) for every function \(H \in H\), then there exists an isometry \(\varphi: (J_1, d_{W_1}) \to (J_2, d_{W_2})\) such that \(\rho\) and \(\rho^{-1}\) are measure preserving, and \(W_1\) and \(W_2\) are equal \(\mu_1^2\)-almost everywhere.

### 3.3.2 Kernels based on chirotopes

We now deduce Theorem 13 from Theorem 4 by studying kernels coming from chirotopes. We let \(\chi\) be the map that sends a triple of points in \(\mathbb{R}^2\) to their orientation. We consider kernels of the form \((\text{supp} \mu, \mu, \chi)\), and let \(d_{\chi, \mu}\) be the associated neighborhood pseudo distance.\(^4\)

**Purity.** Given two distinct points \(a\) and \(b\) in \(\mathbb{R}^2\), we let \((ab)\) be the line through \(a\) and \(b\).

**Lemma 3.7.** Let \(\mu\) be a measure on \(\mathbb{R}^2\). If \(\text{supp} \mu\) has non-empty interior, then the kernel \((\text{supp} \mu, \mu, \chi)\) is twin-free.

**Proof.** Let \(B\) be an open ball contained in \(\text{supp} \mu\), and consider two distinct points \(a\) and \(b\) in \(\text{supp} \mu\). There exists a line separating \(a\) from \(b\) and intersecting \(B\) (for otherwise \(B\) would have to be contained in the line \((ab)\)). Let \(x\) and \(y\) be two distinct points in \((ab) \cap B\). By continuity of the determinant expressing orientations, there exists a positive real \(\epsilon\) such that any line secant to both \(B(x, \epsilon)\) and \(B(y, \epsilon)\) also separates \(a\) from \(b\). This implies that for any \(x' \in B(x, \epsilon)\) and \(y' \in B(y, \epsilon)\), we have \(\chi(x', y', a) \neq \chi(x', y', b)\).

Since \(\mu^2(B(x, \epsilon) \times B(y, \epsilon))\) is positive, it follows that \(a\) and \(b\) are not twins.

**Topologies.** By Lemma 3.7, if the support of a measure \(\mu\) has non-empty interior, then the kernel \((\text{supp} \mu, \mu, \chi)\) is twin-free and \(d_{\chi, \mu}\) is a distance. To show that this kernel is pure, it remains to control the topology induced by \(d_{\chi, \mu}\) on \(\text{supp} \mu\).

**Lemma 3.8.** Let \(\mu\) be a compactly supported measure that charges no line. If \(\text{supp} \mu\) has non-empty interior, then the topologies induced on \(\text{supp} \mu\) by \(d_{\chi, \mu}\) and \(|\cdot|_2\) are equivalent.

**Proof.** We first remark that \(d_{\chi, \mu}\) is a distance thanks to Lemma 3.7. We next argue that \(d_{\chi, \mu}\) is continuous toward \(|\cdot|_2\). To do so, we consider a sequence \((x_n)\) of points in \(\mathbb{R}^2\) converging to some point \(x\) in the sense that \(\lim_{n \to \infty} \|x_n - x\|_2 = 0\), and we prove that we also have \(\lim_{n \to \infty} d_{\chi, \mu}(x_n, x) = 0\). For every pair \((y, z)\) in \(\text{supp} \mu^2\) such that \(x, y\) and \(z\) are not aligned, the set of points \(x' \in \mathbb{R}^2\) satisfying the equation \(\chi(x, y, z) = \chi(x', y, z)\) is an open half-space containing \(x\). Consequently, \(\chi(x_n, y, z)\) is eventually equal to \(\chi(x, y, z)\). It follows that the sequence \(f_n(y, z) = \chi(x, y, z) - \chi(x_n, y, z)\) tends to \(0\) for \(\mu^2\)-almost every pair \((y, z)\) in \(\text{supp} \mu^2\). Indeed, this last statement is true if \(x, y\) and \(z\) are not aligned and the set of pairs \((y, z)\) aligned to \(x\) is a \(\mu^2\)-nullset because \(\mu\) does not charge lines. We conclude by an application of the dominated convergence theorem that the sequence \(d_{\chi, \mu}(x_n, x) = \int_{\text{supp} \mu^2} f_n(y, z) d\mu(y, z)\) tends to \(0\).

To conclude, it suffices to prove that if \(d_{\chi, \mu}(x_n, x)\) tends to \(0\) for some sequence \((x_n)_{n \in \mathbb{N}}\) in \(\text{supp} \mu^N\) and \(x \in \text{supp} \mu\) then \(\|x_n - x\|_2\) tends to \(0\) when \(n\) goes to infinity. We use a classical compactness argument. Assume for the sake of contradiction that there is a sequence \((d_{\chi, \mu}(x_n, x))_{n \in \mathbb{N}}\) that tends to \(0\) while \((\|x_n - x\|_2)_{n \in \mathbb{N}}\) does not. Since \(\text{supp} \mu\) is compact, it is possible to extract a subsequence \((x_{\phi(n)})_{n \in \mathbb{N}}\) that converges with respect to \(|\cdot|_2\) to a limit \(y \in \text{supp} \mu\) different from \(x\). Then, as seen above, \(d_{\chi, \mu}(x_{\phi(n)}, y) \to 0\) and \(d_{\chi, \mu}(x, y) = 0\). Since \(d_{\chi, \mu}\) is a distance, it follows that \(x = y\), which yields a contradiction.

**Corollary 14.** If \(\mu\) is a measure that charges no line and such that \(\text{supp} \mu\) is compact and has non-empty interior in \(\mathbb{R}^2\), then the kernel \((\text{supp} \mu, \mu, \chi)\) is pure.

**Proof.** By Lemma 3.7, we already know that \((\text{supp} \mu, \mu, \chi)\) is twin-free, and therefore that \(d_{\chi, \mu}\) is a distance. By Lemma 3.8, this distance defines the same topology on \(\text{supp} \mu\) as the Euclidean distance, so \((\text{supp} \mu, d_{\chi, \mu})\) is complete and separable. Moreover, any open ball for \(d_{\chi, \mu}\) contains an open ball for \(|\cdot|_2\) so \(\mu\) has full support.

---

\(^4\)We depart here from the notation introduced in Equation (12) because we manipulate several kernels based on the function \(\chi\), so we need to lift the ambiguity.
Alignments. To study how the map $\rho$: supp $\mu_1 \to$ supp $\mu_2$ provided by Theorem 13 transports alignments, we reformulate alignments in topological terms. Let us define the sets
\[ T^+ = \{(a, b, c) \in (\mathbb{R}^2)^3 : \chi(a, b, c) = 1\} \quad \text{and} \quad T^- = \{(a, b, c) \in (\mathbb{R}^2)^3 : \chi(a, b, c) = -1\}. \]
We define $\text{cl}_{\|\cdot\|} (X)$ and $\partial_{\|\cdot\|} X$ to be the topological closure and the boundary of a set $X$ for the topology induced by the Euclidean distance, respectively. From the expression of the orientation of a triple of points as a determinant, it comes
\[ \{(a, b, c) \in (\mathbb{R}^2)^3 : \chi(a, b, c) = 0\} = \partial_{\|\cdot\|} T^+ = \partial_{\|\cdot\|} T^- = \text{cl}_{\|\|} (T^+) \cap \text{cl}_{\|\|} (T^-). \]
\begin{equation}
\text{(13)}
\end{equation}
We use a local version of this characterization of alignment, where we restrict $T^+$ or $T^-$ to the support of a measure $\mu$. Note that $(\text{supp } \mu)^3$ may contain isolated aligned triples or other pathologies, so we have to take some care; we again rely on the assumption that supp $\mu$ has non-empty interior.

Lemma 3.9. Let $X$ be a subset of $\mathbb{R}^2$ that contains an open ball $B$. A triple $t = (x, y, z) \in X^3$ with $x \in B$ is aligned if and only if it is in $\text{cl}_{\|\cdot\|} (T^+ \cap X^3) \cap \text{cl}_{\|\cdot\|} (T^- \cap X^3)$.

Proof. If $t$ is aligned, then there exist $x'$ and $x''$ both in $B$ arbitrarily close to $x$, and separated by the line $(yz)$. It follow that exactly one of $(x', y, z)$ and $(x'', y, z)$ belongs to $T^+ \cap X^3$, and the other belongs to $T^- \cap X^3$. This implies that $t \in \text{cl}_{\|\cdot\|} (T^+ \cap X^3) \cap \text{cl}_{\|\cdot\|} (T^- \cap X^3)$. The other direction follows from the fact that $\text{cl}_{\|\cdot\|} (T^+ \cap X^3) \cap \text{cl}_{\|\cdot\|} (T^- \cap X^3) \subseteq \text{cl}_{\|\cdot\|} (T^+) \cap \text{cl}_{\|\cdot\|} (T^-)$ and Equation (13).

Proof of Theorem 4. We can now prove that if $\mu_1$ and $\mu_2$ are two compactly supported measures of $\mathbb{R}^2$ that charge no line, whose supports have non-empty interiors, and such that $\ell_{\mu_1} = \ell_{\mu_2}$, then there exists a projective transformation $f$ such that $\mu_2 \circ f = \mu_1$.

Proof of Theorem 4. By Corollary 14, the kernels $(\text{supp } \mu_1, \mu_1, \chi)$ are pure. Thus, by Theorem 13, there exists a measure-preserving isometry $\rho$: $(\text{supp } \mu_1, d_{\chi, \mu_1}) \to (\text{supp } \mu_2, d_{\chi, \mu_2})$ such that $\chi$ and $\chi^p$ are equal $\mu_1^p$-almost everywhere. Moreover, Lemma 3.8 ensures that $\rho$ is an homeomorphism from $(\text{supp } \mu_1, \| \cdot \|_2)$ to $(\text{supp } \mu_2, \| \cdot \|_2)$. It remains to analyze how $\rho$ transports alignments.

First, let us remark that $\rho^3 (T^+ \cap \text{supp } \mu_1^3)$ and $T^- \cap \text{supp } \mu_2^3$ are disjoint. To prove this, we note that the intersection of these two sets is open in $\text{supp } \mu_2^3$ and has $\mu_2^3$-measure 0: indeed, we see that $\chi$ and $\chi^p$ disagree on every element of $(T^+ \cap \text{supp } \mu_1^3) \cap (\rho^{-1})^3 (T^- \cap \text{supp } \mu_2^3)$, and therefore
\[ \mu_1^3 ((T^+ \cap \text{supp } \mu_1^3) \cap (\rho^{-1})^3 (T^- \cap \text{supp } \mu_2^3)) = 0, \]
which implies that $\mu_2^3 (\rho^3 (T^+ \cap \text{supp } \mu_1^3) \cap (T^- \cap \text{supp } \mu_2^3)) = 0$. The conclusion follows because $\mu_2^3$ has full support on $\text{supp } \mu_2^3$. A symmetric argument yields that $\rho^3 (T^- \cap \text{supp } \mu_2^3)$ and $T^+ \cap \text{supp } \mu_2^3$ are also disjoint.

Now, consider an aligned triple $t = (x, y, z) \in \text{supp } \mu_1^3$ where $x$ belongs to some open ball $B_1$ contained in $\text{supp } \mu_1$. From Lemma 3.9, it comes that $t \in \text{cl}_{\|\cdot\|} (T^+ \cap \text{supp } \mu_1^3) \cap \text{cl}_{\|\cdot\|} (T^- \cap \text{supp } \mu_2^3)$. Thus, $\rho(t) \in \text{cl}_{\|\cdot\|} (\rho^3 (T^+ \cap \text{supp } \mu_1^3) \cap (T^- \cap \text{supp } \mu_2^3))$. The disjoinedness properties established in the previous paragraph imply that
\[ \rho^3 (T^- \cap \text{supp } \mu_1^3) \subseteq \mathbb{R}^2 \setminus T^+ = \text{cl}_{\|\cdot\|} (T^-) \quad \text{and} \quad \rho^3 (T^+ \cap \text{supp } \mu_2^3) \subseteq \mathbb{R}^2 \setminus T^- = \text{cl}_{\|\cdot\|} (T^+), \]
so $\rho(t) \in \text{cl}_{\|\cdot\|} (T^-) \cap \text{cl}_{\|\cdot\|} (T^+)$. Since $\rho(x)$ belongs to $\rho(B_1)$, which is an open ball contained in $\text{supp } \mu_2$, Lemma 3.9 ensures that $\rho(t)$ is aligned.

So $\rho$ preserves alignments on every triple $(x, y, z) \in \text{supp } \mu_1^3$ with $x \in B_1$. Recall that $B_2 = \rho(B_1)$ is an open, convex set contained in $\text{supp } \mu_2$. We show that $\rho$ preserves alignments in general by a density argument. Let $Q = abcd$ be a convex quadrilateral contained in $B_1$ and such that $(ab) \cap (cd)$ is a unique
point \( e \), contained in \( B_1 \), and \((ad) \cap (be)\) is a unique point \( f \), contained in \( B_1 \). We now subdivide \( Q \), as depicted on the right, by defining \( x = (ae) \cap (bd) \), then introducing the intersections of \((ex)\) with \((ad)\) and \((be)\), and the intersections of \((fx)\) with \((ab)\) and \((cd)\). This produces four new convex quadrilaterals tiling \( Q \). Remark that for any of these new quadrilaterals, the lines supporting opposite sides also intersect in \( e \) and \( f \). We apply this subdivision procedure recursively to any new quadrilateral produced, and let \( A \) be the (infinite) set of vertices of all the quadrilaterals obtained this way. The set \( A \) is dense in our initial quadrilateral \( Q \); indeed, the projective transformation that maps \( a \) to \((0,0)\), \( b \) to \((1,0)\), \( c \) to \((1,1)\) and \( d \) to \((0,1)\) maps \( A \) to the grid \( \{(\frac{k}{2^j}, \frac{j}{2^k}) \mid k \in \mathbb{N} \text{ and } 0 \leq i, j \leq 2^k \} \). (Note that under this transform, \( e \) and \( f \) are mapped to the line at infinity.)

Now, observe that \((\rho(a)\rho(b))\) and \((\rho(c)\rho(d))\) intersect in a unique point, namely \( \rho(e) \in \text{supp } \mu_2 \) (note that \( \rho(\text{supp } \mu_1) \) cannot be contained in a line because \( \rho \) is measure preserving and \( \mu_2 \) does not charge lines). Similarly, \((\rho(a)\rho(d))\) and \((\rho(b)\rho(c))\) intersect in a unique point, which is \( \rho(f) \in \text{supp } \mu_2 \). We perform a similar recursive construction in \( B_2 \), starting from the quadrilateral \( \rho(a)\rho(b)\rho(c)\rho(d) \), and let \( A' \) be the set of vertices obtained.

Let \( p \) be the unique projective transformation that maps \( a \) to \( \rho(a) \), \( b \) to \( \rho(b) \), \( c \) to \( \rho(c) \) and \( d \) to \( \rho(d) \). In particular, \( p \) preserves the colinearity of points in \( \mathbb{R}^2 \). This implies that if \( x \in A \), then \( \rho(x) = p(x) \) as all points in \( A \) and in \( A' \) are defined from \( Q \) and from \((\rho(a), \rho(b), \rho(c), \rho(d)) = (\rho(a), p(b), p(c), p(d))\) using only colinearity properties. Hence \( p_{\Omega} = \rho_{\Omega} \) by continuity.

It remains to show that \( p(\eta) = \rho(\eta) \) for every \( \eta \in \text{supp } \mu_1 \). Let \( \eta \in \text{supp } \mu_1 \) and consider two lines \( L_1 \) and \( L_2 \) that both intersect the interior of \( Q \) and such that \( L_1 \cap L_2 = \{y\} \). For \( i \in \{1, 2\} \), let \( x_i \) and \( z_i \) be two distinct points in \( L_i \cap Q \); in particular \( p(x_i) = \rho(x_i) \) and \( p(z_i) = \rho(z_i) \). By definition, \( p \) preserves colinearity and since \( x_1, x_2 \in B_1 \), both triples \( p^i(x_i, y, z_i) \) are also aligned. It follows that

\[
\rho(y) = (\rho(x_1)\rho(z_1)) \cap (\rho(x_2)\rho(z_2)) = (p(x_1)p(z_1)) \cap (p(x_2)p(z_2)) = p(y),
\]

which completes the proof.

\[ \square \]

### 3.3.3 Rigidity for kernels (proofs)

We now prove the rigidity results stated in Section 3.3.1.

#### Step functions.

We first argue that any kernel can be approximated by a step function.

**Lemma 3.10.** Let \( (J, \mu, W) \) be a kernel. For every positive real number \( \varepsilon \), there exists a step function \( V \) on \( (J, \mu) \) such that \( \|W - V\|_1 \leq \varepsilon \).

**Proof.** It is well known in measure theory that for every function \( W \) and every positive \( \varepsilon \), there exists a function \( V : J^3 \to \mathbb{R} \) that is measurable, has finite image (i.e., \( V(J^3) \) is finite) and satisfies \( \|W - V\|_\infty \leq \varepsilon/2 \). Let us write \( V = \sum_{i=1}^k a_i 1_{A_i} \), where \( a_i \) is a nonzero real number and \( 1_{A_i} \) the indicator function of a measurable set \( A_i \), for each \( i \in [k] \).

Let \( B \) be the set of boxes of the form \( P_1 \times P_2 \times P_3 \), where \( P_1 \), \( P_2 \) and \( P_3 \) are measurable subsets of \( J \) and let \( X \) be the set of finite unions of elements of \( B \). For every \( i \in [k] \), there is a set \( B_i \in X \) such that \( \mu(A_i \triangle B_i) \leq \frac{\varepsilon}{2k|A_i|} \). (A proof of this fact is presented in Appendix, Lemma A.1.) The function \( U = \sum_{i=1}^k a_i 1_{B_i} \) is a step function as a linear combination of step functions. Moreover,

\[
\|U - V\|_1 \leq \sum_{i=1}^k |a_i| \cdot \|1_{A_i} - 1_{B_i}\|_1 = \sum_{i=1}^k |a_i| \cdot \mu(A_i \triangle B_i) \leq \frac{\varepsilon}{2}.
\]

Consequently, \( \|W - U\|_1 \leq \|W - V\|_1 + \|V - U\|_1 \leq \varepsilon \), which finishes the proof.

\[ \square \]
Induced step functions. Let \( \mu_n^\mu \) be the counting measure on \([n]\). As reported earlier (in Subsection 3.3.1), we know that \((\mu_n^\mu, H(W, S))\) is a step function for the partition of \([n]\) into singletons. We now bound the distance between this step function and \((J, \mu, W)\). Thanks to Lemma 3.10, it is sufficient to deal with the case where \((J, \mu, W)\) is also a step function. We use the following (standard) terminology. An atom of a measure \(\mu\) is a \(\mu\)-measurable set \(A\) with \(\mu(A) > 0\) and such that every \(\mu\)-measurable subset of \(A\) has measure either \(\mu(A)\) or 0. A measure is atom-free if it admits no atom.

**Lemma 3.11.** Let \((J, \mu, W)\) be a step function and let \((P_1, \ldots, P_m)\) be a partition of \(J\) such that \(W\) is constant on \(P_i \times P_j \times P_k\) for any \((i, j, k) \in [m]^3\). For every integer \(n\) and every tuple \(S = (x_1, \ldots, x_n) \in J^n\),

\[
d(W, H(W, S)) \leq 6 \sum_{i=1}^m |\mu(P_i) - |\{j \in [n]: x_j \in P_i\}||/n\cdot ||W||_\infty.
\]

**Proof.** We first eliminate any atom the measure \(\mu\) may have by defining an atom-free measurable space \((J_0, \mu_0)\) and a measure-preserving map \(\phi_1: J_0 \rightarrow J\). Now, let us write

\[Q_i = \{j \in [n]: x_j \in P_i\} \text{ and } n_i = |Q_i|\]

For \(i \in [m]\), we set \(a_i = \min\{\mu(P_i), \mu_0^\mu(Q_i)\}\). Since \(\mu_0(\phi_1^{-1}(P_i)) = \mu(P_i) \geq a_i\), there is a subset \(R_i \subseteq \phi_1^{-1}(P_i)\) such that \(\mu_0(R_i) = a_i\). The set \(J'_0 = J_0 \setminus \bigcup_{i=1}^m R_i\) has measure \(1 - \sum_{i=1}^m a_i = \sum_{i=1}^m (\mu_0^\mu(Q_i) - a_i)\). A now classical theorem of measure theory, due to Sikorski [34], assures that we can partition \(J'_0\) into \(m\) measurable subsets \(T_1, \ldots, T_m\) such that \(\mu_0(T_i) = \mu_0^\mu(Q_i) - a_i\) for every \(i \in [m]\). (A proof that such a partition exists is presented in Appendix, Lemma A.2.)

We now construct a measure-preserving function \(\phi_2\) such that \(\phi_2(R_i \cup T_i) = Q_i\) for each \(i \in [m]\). Recall that \((Q_1, \ldots, Q_m)\) is a partition of \([n]\). We know that \(\mu_0(R_i \cup T_i) = \mu_0^\mu(Q_i) = n_i/n\) for each \(i \in [m]\), so there is a partition \((B_j^i)_{j \in Q_i}\) of \(R_i \cup T_i\) into \(n_i\) parts each of \(\mu_0^\mu\)-measure \(1/n\), which are indexed by the elements of \(Q_i\). If \(j \in Q_i\), then we set \(\phi_2(y) = j\) for every \(y \in B_j^i\). Doing this for each \(i \in [m]\) naturally defines a function \(\phi_2\) from \(J_0\) to \([n]\). (Indeed, for every \(x \in J_0\) there is a unique pair \((i, j) \in [m] \times [n]\) such that \(x \in B_j^i\), and we set \(\phi_2(x) = j\).) For convenience, we note that for each \(j \in [n]\), there is exactly one index \(i \in [m]\) such that \(B_j^i\) is defined: we call \(i(j)\) this index.

The function \(\phi_2\) satisfies that \(\phi_2(R_i \cup T_i) = Q_i\) for each \(i \in [m]\). Moreover, it is measure preserving since \(\mu_0(\phi_2^{-1}(A)) \leq \sum_{j \in A} \mu_0^\mu(B_j^{i(j)}) = |A|/n = \mu_0^\mu(A)\) for every \(A \subseteq [n]\). To deduce our assertion, it suffices to prove that

\[
\left\| W^{\phi_1} - H(W, S)^{\phi_2} \right\|_1 \leq 6 \sum_{i=1}^m |\mu(P_i) - \mu_0^\mu(Q_i)| \cdot ||W||_\infty.
\]

If \(a\) belongs to \(R_i\) for some \(i \in [m]\), then by construction \(\phi_1 (a) \in P_i\) and moreover \(\phi_2(a) \in Q_i\), that is, \(x_{\phi_2(a)} \in P_i\). Consequently, for every \((i, j, k) \in [m]^3\) the functions \(W^{\phi_1}\) and \(H(W, S)^{\phi_2}\) are equal (and constant) on \(R_i \times R_j \times R_k\).

It follows that \(W^{\phi_1}\) and \(H(W, S)^{\phi_2}\) are equal everywhere on the set \(X = (J'_0 \times J_0 \times J_0) \cup (J_0 \times J'_0 \times J_0) \cup (J_0 \times J_0 \times J'_0)\), which has measure \(\mu_3\) at most \(3\mu_0(J'_0) = 3 \sum_{i=1}^m (\mu_0^\mu(Q_i) - a_i) \leq 3 \sum_{i=1}^m |\mu(P_i) - \mu_0^\mu(Q_i)|\). Consequently,

\[
\left\| W^{\phi_1} - H(W, S)^{\phi_2} \right\|_1 \leq \int_X |W^{\phi_1} - H(W, S)^{\phi_2}| d\mu_3 \leq \int_X |W^{\phi_1}| d\mu_3 + \int_X |H(W, S)^{\phi_2}| d\mu_3 \leq 2 \cdot ||W||_\infty \cdot \mu_3(X) \leq 6 ||W||_\infty \sum_{i=1}^m |\mu(P_i) - \mu_0^\mu(Q_i)|.
\]

The statement follows. □

---

5If \(\mu\) is atom-free then we may take \((J_0, \mu_0) = (J, \mu)\) and \(\phi_1\) equal to the identity; otherwise, we set \(J_0 = J \times [0, 1]\), we let \(\mu_0\) be the product measure of \(\mu\) and the Lebesgue measure on \([0, 1]\), and we let \(\phi_1\) be the projection of \(J_0\) on its first coordinate.

6This result is often, and apparently wrongly, attributed to Sierpiński.
Random step functions. To control how well $H(W, n)$ approximates $W$, we use the following lemma.

Lemma 3.12. For every kernel $(J, \mu, W)$ and every integer $n$,

$$|E[\|H(W, n)\|_1 - \|W\|_1| \leq \frac{3}{n} \|W\|_\infty.$$  

Proof. Let $S = (x_1, \ldots, x_n)$ be a $\mu^n$-random tuple of $J^n$. The expected value $E$ of $\|H(W, S)\|_1$ is equal to

$$\int_{\mu} \frac{1}{n} \sum_{1 \leq i, j, k \leq n} |W(x_i, x_j, x_k)| d\mu^n(S) = \frac{1}{n} \sum_{1 \leq i, j, k \leq n} I_{i, j, k},$$

where $I_{i, j, k}$ is the integral $\int_{\mu} |W(x_i, x_j, x_k)| d\mu^n(S)$. First note that $0 \leq I_{i, j, k} \leq \|W\|_\infty$ for every $(i, j, k) \in [n]^3$. If moreover $i$, $j$, and $k$ are pairwise different, then $I_{i, j, k} = \|W\|_1$. The number of triples of $[n]^3$ with pairwise different elements is greater than $n^3 - 3n^2$. It follows that $(n^3 - 3n^2) \|W\|_1 \leq n^3 E \leq (n^3 - 3n^2) \|W\|_1 + 3n^2 \|W\|_\infty$, and further $-\frac{3}{n} \|W\|_1 \leq E - \|W\|_1 \leq \frac{3}{n} \|W\|_\infty$, which yields the conclusion since $\|W\|_1 \leq \|W\|_\infty$. \qed

We can now prove that random step functions are good approximations relatively to our distance.

Lemma 3.13. Let $(J, \mu, W)$ be a kernel. For every positive integer $n$, we consider the random kernel $([n], \mu^n, H(W, n))$. The random sequence $(d(W, H(W, n)))_n$ almost surely tends to 0 as $n$ goes to infinity.

Proof. Let us first assume that $W$ is a step function. We fix a partition $(P_1, \ldots, P_m)$ of $J$ such that $W$ is constant on $P_i \times P_j \times P_k$ for every $(i, j, k) \in [m]^3$ and apply Lemma 3.11 to obtain, for any $n$-tuple $S$, the upper bound:

$$d(W, H(W, S)) \leq 6 \sum_{i=1}^m \left| \mu(P_i) - \frac{|\{j \in [n]: x_j \in P_i]\}}{n} \right| \|W\|_\infty. \quad (14)$$

Let us now consider a $\mu^n$-random tuple $S$ and set $Q_i = \{j \in [n]: x_j \in P_i\}$ and $n_i = |Q_i|$. For each $i \in [m]$, the parameter $n_i$ follows a binomial law of parameter $\mu(P_i)$. Fix $\varepsilon > 0$. By Hoeffding's inequality, the probability that $|\mu(P_i) - \frac{n_i}{n}| \geq \varepsilon$ is at most $2e^{-2\varepsilon^2 n}$. Thus the union bound yields that $d(W, H(W, S)) \leq 6m \varepsilon \|W\|_\infty$ with probability at least $1 - 2m e^{-2\varepsilon^2 n}$. Hence, $d(W, H(W, n))$ goes almost surely to 0 when $n$ goes to infinity.

Let us now consider the general case. By Lemma 3.10, there is a step function $V$ on $(J, \mu)$ such that $\|W - V\|_1 \leq \varepsilon$. For every positive integer $n$, one can couple the random variables $H(V, n)$ and $H(W, n)$ such that

$$E[\|H(V, n) - H(W, n)\|_1] \leq \frac{3}{n} \|W - V\|_1. \quad (15)$$

Indeed, let $S = (x_1, \ldots, x_n)$ be a single $\mu^n$-random tuple of $J^n$, and note that $H(V, S) - H(W, S) = H(V - W, S)$. Lemma 3.12 applied to $V - W$ yields Equation (15). Since $V$ is a step function, we know from the first part of the proof that when $n$ goes to infinity, the random sequence $(d(V, H(V, n)))_n$ almost surely goes to 0. Let $N$ be large enough to ensure that whenever $n \geq N$, both $E(d(V, H(V, n))) \leq \varepsilon$ and $\frac{3}{n} \|V - W\|_\infty \leq \varepsilon$ hold. It follows that for every $n \geq N$,

$$E[d(W, H(W, n))] \leq E[d(W, V) + d(V, H(V, n)) + d(H(V, n), H(W, n))] \leq d(W, V) + E(d(V, H(V, n))) + E(\|H(V, n) - H(W, n)\|_1) \leq \|W - V\|_1 + E(d(V, H(V, n))) + \frac{3}{n} \|V - W\|_\infty \leq 3\varepsilon.$$

The statement follows. \qed

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Proof of Theorem 11. We can now prove the first rigidity result that we stated: if \((J_1, \mu_1, W_1)\) and \((J_2, \mu_2, W_2)\) are two kernels such that \(t(H, W_1) = t(H, W_2)\) for every function \(H \in \mathcal{H}\), then \(d(W_1, W_2) = 0\).

Proof of Theorem 11. The assumption implies that for every positive integer \(n\), the two random variables \(H(W_1, n)\) and \(H(W_2, n)\) have the same distribution. Consequently, if \(H_n\) is a random function equivalent to both \(H(W_1, n)\) and \(H(W_2, n)\), then by Lemma 3.13 both \(d(W_1, H_n)\) and \(d(W_2, H_n)\) almost surely tend to 0. The triangular inequality \(d(W_1, W_2) \leq d(W_1, H_n) + d(H_n, W_2)\) thus ensures that \(d(W_1, W_2) = 0\).

Kernel isomorphisms. We next show that there is an isomorphism between (almost all) the sets associated to these kernels that preserves (almost everywhere) the characteristic of the kernels, that is, their measures and their functions (Proposition 12). We start with an analogue of a classical result on kernels, which provides a weaker conclusion.

Lemma 3.14. If \((J_1, \mu_1, W_1)\) and \((J_2, \mu_2, W_2)\) are two kernels such that \(d(W_1, W_2) = 0\), then there exist a probability space \((J, \mu)\) and for each \(i \in \{1, 2\}\) a measure-preserving map \(\phi_i : J \to J_i\) such that

- for every \(i \in \{1, 2\}\) and every \(\mu\)-measurable set \(A \subseteq J\), the set \(\phi_i(A)\) is \(\mu_i\)-measurable; and
- \(W_2^{\phi_1}(x, y, z) = W_1^{\phi_1}(x, y, z)\) and \(W_1^{\phi_2}(x, y, z) = W_2^{\phi_2}(x, y, z)\) for \(\mu^3\)-almost every \((x, y, z) \in J^3\).

Proof. We only sketch the argument, as it is a straightforward extension of results already published, as referenced in what follows. We may first assume that \(J_1 = [0, 1] = J_2\). A proof of this fact for functions of two variable was given by Janson [22, Proof of Theorem 7.1]. His argument extends directly to functions of three variables and, for that matter, to any finite number of variables. (We point out that although Janson assume a kernel to be symmetric in its two variables, in the proof of Theorem 7.1 (and, more specifically, in the proof of Lemma 7.3), this assumption is used only to ensure that the obtained function is again symmetric (and thus a kernel in Janson’s sense), which is not needed here.)

Now a direct adaptation of the proof of Theorem 8.13 in the book by Lovász [25, p. 136] gives the lemma. We just give an outline of the argument. We aim to show the statement of the theorem for \(J = J_1 \times J_2\), and \(\phi_i\) being the projection of \(J\) on \(J_i\) for \(i \in \{1, 2\}\). We know that \(d(W_1, W_2) = \inf_{\mu} \|W_1^\phi - W_2^\phi\|_1^\mu\), where \(\mu\) ranges over all coupling measures of \(J = J_1 \times J_2\). It suffices to show that this last infimum is in fact a minimum to deduce the statement. As we assumed that \(J_1 = [0, 1] = J_2\), the space of coupling measures is compact in the weak topology. Consequently, it is enough to show that the function \(\mu \mapsto \|W_1^\phi - W_2^\phi\|_1^\mu\) is lower semicontinuous, i.e., if \((\mu_n)\) weakly converges to \(\mu\) then

\[
\liminf_n \|W_1^\phi - W_2^\phi\|_1^{\mu_n} \geq \|W_1^\phi - W_2^\phi\|_1^\mu.
\]

This last inequality is Inequality (8.21) on p. 137 of loc. cit. and the proof follows as in the book.

The twin-free case (proof of Proposition 12). We can now prove a stronger rigidity: given two twin-free kernels \((J_1, \mu_1, W_1)\) and \((J_2, \mu_2, W_2)\), if \(t(H, W_1) = t(H, W_2)\) for every function \(H \in \mathcal{H}\), then there exist two sets \(N_1 \subseteq J_1\) and \(N_2 \subseteq J_2\) with \(\mu_1(N_1) = 0 = \mu_2(N_2)\) and an invertible and measure-preserving map \(\rho : J_1 \setminus N_1 \to J_2 \setminus N_2\) such that

1. \(\rho^{-1}\) is measure preserving; and
2. \(W_1\) and \(W_2\) are equal \(\mu_1\)-almost everywhere.

Proof of Proposition 12. Theorem 11 ensures that Lemma 3.14 applies: let \((J, \mu)\) and \(\phi_1, \phi_2\) be the probability space and the applications given by this lemma, respectively. For \(i \in \{1, 2\}\), we set \(J_i = \phi_i(J)\) and \(N_i = J_i \setminus J_i\). So \(\mu_i(N_i) = 0\) because \(\phi_i\) is measure preserving and \(\phi_i^{-1}(J_i) = J_i\).

We start by showing that if two elements of \(J\) have the same image by \(\phi_1\), then they must have the same image by \(\phi_2\); that is, \(\phi_2(\phi_1^{-1}(\{x\}))\) is a singleton for every \(x \in J_1\). Indeed, suppose that \(\phi_1^{-1}(\{x\})\) contains two distinct elements \(a\) and \(b\). Then \(W_1^{\phi_1}(a, y, z) = W_2^{\phi_1}(b, y, z)\) for every \((y, z) \in J_2\). Furthermore, we know that \(W_1^{\phi_1}(a, y, z) = W_2^{\phi_2}(a, y, z)\) and \(W_1^{\phi_1}(b, y, z) = W_2^{\phi_2}(b, y, z)\) for \(\mu^2\)-almost
every pair \((y, z) \in J^2\). Consequently, \(W_2^{\phi_2}(a,y,z) = W_2^\phi(b,y,z)\) for \(\mu^2\)-almost every pair \((y, z) \in J^2\).

This implies that \(W_2(\phi_2(a), y', z') = W_2(\phi_2(b), y', z')\) for \(\mu^2\)-almost every pair \((y', z') \in J^2_2\), because \(\mu(J) = \mu(\phi_2^2(J)) = \mu_2(\phi_2(J))\). (The last equality follows from the fact that \(\phi_2\) is measure preserving.) Since \(W_2\) is twin-free, we deduce that \(\phi_2(a) = \phi_2(b)\). Therefore, we can define a map \(\rho: J_1 \to J_2\) by setting \(\rho(x)\) to be the unique element of \(\phi_2(\phi_1^{-1}(\{x\}))\).

Now, observe that there exists a subset \(N\) of \(J_1^3\) with \(\mu_3^1(N) = 0\) such that

- \(\tilde{J}_1^3 \setminus N \subseteq \phi_1(J_1^3)\);
- \((x, y, z) \mapsto (\rho(x), \rho(y), \rho(z))\) is defined everywhere on \(\tilde{J}_1^3 \setminus N\); and
- \(W_2^{\phi_2}(x, y, z) = W_1^{\phi_1}(x, y, z)\) whenever \((\phi_1(x), \phi_1(y), \phi_1(z)) \notin N\).

For \((x_1, y_1, z_1) \in \tilde{J}_1^3 \setminus N\), let \((x, y, z) \in J^2\) such that \(\phi_1(x) = x_1\), \(\phi_1(y) = y_1\) and \(\phi_1(z) = z_1\). Then \(\rho(x_1) = \phi_2(x), \rho(y_1) = \phi_2(y)\) and \(\rho(z_1) = \phi_2(z)\). Therefore \(W_1^\phi(x_1, y_1, z_1) = W_2^\phi(x, y, z) = W_1^\phi(x_1, y_1, z_1)\), which yields \(\mathbf{2}\).

Let us show that \(\rho\) is measure preserving. We observe that if \(A \subseteq J_2\), then \(\rho^{-1}(A) = \phi_1(\phi_2^{-1}(A))\).

Indeed, by the definitions

\[
\rho^{-1}(A) = \{ x \in \tilde{J}_1 \mid \phi_2(\phi_1^{-1}(\{x\})) \subseteq A \}
= \{ x \in \tilde{J}_1 \mid \phi_1^{-1}(\{x\}) \subseteq \phi_2^{-1}(A) \}
\subseteq \phi_1(\phi_2^{-1}(A)).
\]

Conversely, if \(x \in \phi_1(\phi_2^{-1}(A))\), then there exists \(y \in J\) such that \(\phi_1(y) = x \) and \(\phi_2(y) \in A\). Since \(\phi_1(\phi_2^{-1}(A))\) is a singleton, we deduce that \(\phi_2(\phi_1^{-1}(\{x\})) = \{\phi_2(y)\}\), which is contained in \(A\). This proves the observation.

As a result, it suffices to prove that \(\mu_2(A) = \mu_1(\phi_1(\phi_2^{-1}(A)))\) to infer that \(\mu_1(\rho^{-1}(A)) = \mu_2(\rho(A))\). As \(\phi_1\) and \(\phi_2\) are measure preserving, it is enough to prove that \(\phi_1^{-1}(\phi_1(\phi_2^{-1}(A))) = \phi_2^{-1}(A)\). By definition, the set on the right side is always contained in the set on the left side. For the converse inclusion, fix \(x \in \phi_1^{-1}(\phi_1(\phi_2^{-1}(A)))\) and let us show that \(\phi_2(x) \in A\). There exists \(y \in J\) such that \(\phi_1(y) = \phi_1(x)\) and \(\phi_2(y) \in A\). In particular, \(\phi_2(y) \in \phi_2(\phi_1^{-1}(\phi_1(\{x\})))\) and hence \(\phi_2(\phi_1^{-1}(\phi_1(\{x\}))) = \{\phi_2(y)\}\). However, \(x \in \phi_1^{-1}(\phi_1(\{x\}))\) and thus \(\phi_2(x) = \phi_2(y) \in A\).

To see that \(\rho\) is invertible, we first define \(\rho': J_2 \to \tilde{J}_1\). To this end, one shows similarly as before that \(\phi_1(\phi_2^{-1}(\{x\}))\) is a singleton for every \(x \in J_2\). So \(\rho'\) can be defined as the unique element of \(\phi_1(\phi_2^{-1}(\{x\}))\). Now by symmetry of the roles played by \(\phi_1\) and \(\phi_2\), one sees similarly as before that \(\rho'\) is measure preserving.

It remains to prove that \(\rho'(\rho(x)) = x\) for every \(x \in \tilde{J}_1\). Fix \(x \in \tilde{J}_1\). As \(\phi_2(\phi_1^{-1}(\{x\})) = \{\rho(x)\}\), there exists \(y \in J\) such that \(\phi_1(y) = x \) and \(\phi_2(y) = \rho(x)\). Consequently, \(x \in \phi_1(\phi_2^{-1}(\{\rho(x)\}))\), which is equal to \(\rho'(\rho(x))\). This concludes the proof.

The case of pure kernels (proof of Theorem 13). We finally establish our strongest rigidity theorem for kernels: if \((J_1, \mu_1, W_1)\) and \((J_2, \mu_2, W_2)\) are two pure kernels and \((H, W_1) = (H, W_2)\) for every function \(H \in \mathcal{H}\), then there exists an isometry \(\rho: (J_1, d_{W_1}) \to (J_2, d_{W_2})\) such that \(W_1\) and \(W_2\) are equal \(\mu^2\)-almost everywhere.

Proof of Theorem 13. Let \(\rho: J_1 \setminus N_1 \to J_2 \setminus N_2\) be the map given by Proposition 12 applied to \((J_1, \mu_1, W_1)\) and \((J_2, \mu_2, W_2)\). We first prove that we may restrict \(\rho\) to a set \(D_1\) with \(\mu_1\)-measure one such that if we fix any \(x \in D_1\), then \(W_1(x,y,z) = W_2^\rho(x,y,z)\) for \(\mu_2\)-almost every pair \((y,z) \in J^2_2\). For \(x \in J_1\), we define \(J(x) \subseteq J^2_2\) to be the set of pairs \((y, z)\) such that \(W_1(x,y,z) \neq W_2^\rho(x,y,z)\). Further, let \(A\) be the set composed of each \(x \in J_1\) such that \(\mu_1^2(I(x)) > 0\).

We assert that \(\mu_1(A) = 0\). To prove this, we set \(A_n = \{ x \in J_1 \mid \mu_1^2(I(x)) > \varepsilon \} \) and we notice that \(A = \bigcup_n A_n\) where the union is taken over a decreasing sequence \(\{\varepsilon_n\}_{n \in \mathbb{N}}\) that tends to 0. As the union is countable, it suffices to prove that \(\mu_1(A_n) = 0\) for every \(\varepsilon > 0\) to conclude that \(\mu_1(A) = 0\). Fixing \(\varepsilon > 0\), it follows from the definitions that \(W_1(x,y,z) \neq W_2^\rho(x,y,z)\) for every triple in \(\{ (x, y, z) \mid x \in A, (y,z) \in I(x) \}\), which is a set of \(\mu^2\)-measure at least \(\varepsilon \cdot \mu_1(A)\). Because of Property 2 of Proposition 12, the previous statement implies that \(\varepsilon \cdot \mu_1(A) = 0\), hence \(\mu_1(A) = 0\).

We define \(D_1 = J_1 \setminus N_1 \setminus A\) and \(D_2 = \rho(D_1) = J_2 \setminus N_2 \setminus \rho(A)\). We know that \(\mu_1(D_1) = 1\) and the equality \(\mu_2(D_2) = 1\) follows from the fact that \(\rho^{-1}\) is measure preserving. The restriction \(\rho|_{D_1}: D_1 \to D_2\) of \(\rho\) to \(D_1\)
is an isometry between the metric spaces \((D_1, d_{W_1})\) and \((D_2, d_{W_2})\). Indeed, fixing \((x, x') \in D_1^2\), we know from the construction of \(D_1\) that for \(\mu_1^2\)-almost every pair \((y, z) \in J_1^2\) we have \(W_1(x, y, z) = W_2^\rho(x, y, z)\) and \(W_1(x', y, z) = W_2^\rho(x', y, z)\). So in particular \(W_1(x, y, z) - W_1(x', y, z) = W_2^\rho(x, y, z) - W_2^\rho(x', y, z)\). Consequently,

\[
d_{W_1}(x, x') = \int_{J_1^2} |W_1(x, y, z) - W_1(x', y, z)| \, d\mu_1^2(y, z)
= \int_{J_1^2} |W_2^\rho(x, y, z) - W_2^\rho(x', y, z)| \, d\mu_1^2(y, z)
= \int_{J_1^2} |W_2(\rho(x), y', z') - W_2(\rho(x'), y', z')| \, d\mu_2^2(y', z')
= d_{W_2}(\rho(x), \rho(x')).
\]

This proves that \(\rho_{|D_1}\) is an isometry.

Now we assume that \(\mu_1\) has full support and \((J_2, d_{W_2})\) is complete. In this case, \(\rho_{|D_1}\) extends by continuity to an injective map \(\hat{\rho}\) on \(J_1\). To prove this, it suffices to show that \(\rho_{|D_1}\) is absolutely continuous and \(D_1\) is dense in \((J_1, d_{W_1})\). The absolute continuity follows from the fact that \(\rho_{|D_1}\) is an isometry. The set \(D_1\) is dense in \(J_1\) because every open set included in \(J_1 \setminus D_1\) is an open nullset, and hence is empty as \(\mu_1\) has full support. By continuity of \(d_{W_1}\) and \(d_{W_2}\) towards themselves the extension \(\hat{\rho}\) is an isometry.

To prove the second item, it suffices to apply the previous proof to the inverse \((\rho_{|D_1})^{-1}\) of \(\rho_{|D_1}\), where the roles played by \((J_1, \mu_1, W_1)\) and \((J_2, \mu_2, W_2)\) are inverted. \(\square\)

### 3.4 Flexibility of realizations and the probability that \(k\) random points are in convex position

For limits of order types that can be realized by at least one measure whose support has non-empty interior, the rigidity theorem completely describes the space of realizations: they are the orbit of that one realization under spherical transformations. In general, the situation can be radically different as the following example shows.

**Example 3.1.** Let \(\ell_o\) be the limit of a sequence of sets of points in convex position. This limit assigns the probability 1 to each \(\omega_k\), the order type of \(k\) points in convex position, and 0 to the rest. Every measure with convex support realizes \(\ell_o\); this allows arbitrarily disconnected support, as well as support of any Hausdorff dimension between 0 and 1 (consider a Cantor set on \([0, 1]\) with that dimension and map the interval to the circle).

The limit \(\ell_o\) is exceptionally simple, it obviously maximizes \(\ell(\omega_k)\). One may wonder if this variety of realizations is also exceptional. We construct a different limit with similar realization properties that plays a role in combinatorial geometry as it gets close to minimizing \(\ell(\omega_k)\) for \(k\) large enough.

**Theorem 15.** There exists a limit \(\ell_E\) of order types such that for every \(t \in (0, 1)\), the limit \(\ell_E\) can be realized by a measure with a support of Hausdorff dimension \(t\). Moreover, there is no measure \(\mu\) that realizes \(\ell_E\) and is, on an open set of positive \(\mu\)-measure, absolutely continuous to the Lebesgue measure or to the length measure on a \(C^2\) curve of positive length.

Theorem 15 will follow from Lemma 3.15 for the first statement, and Proposition 17 and Lemma 3.16 for the second statement.

### 3.4.1 Definition of \(\ell_E\)

It is convenient to give two presentations of \(\ell_E\), one geometric and the other combinatorial.

Let us start with the combinatorial definition of \(\ell_E\). Consider the space \(E = \{0, 1\}^\mathbb{N}\) equipped with the coin-tossing measure. For \(u, v \in E\), let \(u \wedge v\) be the longest common prefix of \(u\) and \(v\) and let \(\prec_{lex}\) be the lexicographic order on \(E\). We define \(\ell_E\) as a chirotope \(\chi\) on \(E\). Specifically, let \(u, v, w \in E\) and, without loss of generality, suppose that \(u \prec_{lex} v \prec_{lex} w\). We set \(\chi(u, v, w) = 1\) if \(|u \wedge v| < |v \wedge w|\) and \(\chi(u, v, w) = -1\) otherwise. For any order type \(\omega\) of size \(k\), we let \(\ell_E(\omega)\) be the probability that the
Let us now give a geometric presentation of $\ell_E$; refer to Figure 1. As is usual, let $\{0,1\}^*$ be the collection of all finite binary words. Fix some parameters $a$ and $b$ such that $0 < b < a < \frac{1}{2}$, and define the rectangles $R = [0,1]^2$, $R_0 = [0,a] \times [0,b]$ and $R_1 = [1-a,1] \times [1-b,1]$. For each $i \in \{0,1\}$, let $\varphi_i$ be the affine transform fixing $(i,i)$ and mapping $R$ to $R_i$. To any word $w = i_1i_2\ldots i_n \in \{0,1\}^*$ we associate the set $R_w = \varphi_{i_n} \circ \varphi_{i_{n-1}} \circ \cdots \circ \varphi_1(R)$ and let $\mu^{a,b}$ be the probability measure such that $\mu^{a,b}(R_w) = \frac{1}{2^n}$ for every $w \in \{0,1\}^*$. We notice that $R_w \subset R_0$ if and only if $v$ is a prefix of $w$. Letting $A_n = \bigcup_{w \in \{0,1\}^n} R_w$ for $n \geq 1$, the support of $\mu^{a,b}$ is $A = \bigcap_{n \geq 1} A_n$.

**Lemma 3.15.** If $(a,b) \in (0,\frac{1}{2})^2$ and $b \leq (1-2a)(1-2b)a$, then $\ell_{\mu^{a,b}} = \ell_E$. In particular, $\ell_E$ is a limit of order types.

**Proof.** The measure $\mu^{a,b}$ is the image of the coin-tossing probability on $\{0,1\}^\infty$ by the function $\Psi_{a,b}$ that assigns to $w \in \{0,1\}^\infty$ the unique point in $\bigcap_{n=1} w_n R_{w_n}$, where the intersection is taken over all prefixes $w_n$ of $w$.

We shall prove that every point in $A \cap R_1$ lies above any line spanned by two points in $A \cap R_0$ provided that

$$b \leq (1-2a)(1-2b)a.$$

Since $A$ is stable by the symmetry of center $(\frac{1}{2},\frac{1}{2})$, it would then follow that every point in $A \cap R_0$ lies below any line spanned by two points in $A \cap R_1$. Let us show how this property of $A$ allows us to conclude the proof. Indeed, this property yields that $\ell_{\mu^{a,b}}$ is fully determined. Let $\Psi_{a,b}(u)$, $\Psi_{a,b}(v)$ and $\Psi_{a,b}(w)$ be three pairwise distinct points in $A$ with $u, v, w \in \{0,1\}^\infty$ and assume that $u \triangleright_{\text{lex}} v \triangleright_{\text{lex}} w$. If $|u \wedge v| < |v \wedge w|$, set $p = u \wedge v$. Since $u \triangleright_{\text{lex}} v$, the word $p.0$ is a prefix of $u$ and $p.1$ is a prefix of $v$, and therefore of $w$. It follows that $\Psi_{a,b}(u) \in R_{p.0}$ and $\{\Psi_{a,b}(v), \Psi_{a,b}(w)\} \subset R_{p.1}$. Moreover, the abscissa of $\Psi_{a,b}(v)$ is smaller than that of $\Psi_{a,b}(w)$ because $v \triangleright_{\text{lex}} w$. Consequently, $\chi(\Psi_{a,b}(u), \Psi_{a,b}(v), \Psi_{a,b}(w)) = 1 = \chi_E(u, v, w)$.

The proof that $\chi(\Psi_{a,b}(u), \Psi_{a,b}(v), \Psi_{a,b}(w)) = \chi_E(u, v, w)$ when $|u \wedge v| > |v \wedge w|$ is similar and we omit it.

It remains to prove that $A$ indeed fulfills the property announced. For two distinct points $x, y \in A$, let $\alpha(x, y)$ be the angle between the line $h(x, y)$ and the abscissa axis (so $\alpha(x, y)$ is defined modulo $\pi$). If $x \in R_0$ and $y \in R_1$, then

$$1 - 2b \leq \tan \alpha(x, y) \leq \frac{1}{1 - 2a},$$

since the minimum is obtained when $x_m = (0,b)$ and $y_m = (1,1-b)$, while the maximum is obtained when $x_M = (a,0)$ and $y_M = (1-a,1)$ (see Figure 2, left). The application of a function $\varphi_i$ with $i \in \{1,2\}$ acts as follows

$$\tan \alpha(\varphi_i(x), \varphi_i(y)) = \frac{b}{a} \tan \alpha(x, y).$$

Figure 1: Definition of $\ell_E$.\hfill

As mentioned already in the introduction, the limit of order types \( \ell_E \) was constructed to attack the Erdős-Szemerédi problem of determining \( c_k \). In fact, both upper and lower bounds on \( c_k \) go back to the classical results of Erdős and Szekeres who proved that for every integer \( k \), there exists \( s(k) \) such that any planar point set in general position and of size at least \( s(k) \) contains \( k \) points in convex position. Erdős and Szekeres also gave a construction showing that \( s(k) \geq 2^{k-2} + 1 \) and they conjectured this value to be tight. This bound was nearly achieved in a recent breakthrough of Suk [37] who improved the upper bound on \( s(k) \) to \( 2^{k+6k^{2/3}} \log k \). The next proposition is folklore.

**Proposition 16.** For every integer \( k \geq 4 \) and every limit of order types \( \ell \),

\[
\ell(\omega_k) \geq 2^{-k^2 + o(k^2)}.
\]

**Proof.** Let \( (\omega_n)_{n \in \mathbb{N}} \) be a convergent sequence of order types with limit \( \ell \). The Erdős-Szemerédi theorem ensures that \( p(\omega_k, \omega) \geq \left( \frac{1}{k} \right)^{1/k} \) for any order type \( \omega \) of size \( s(k) \). Let \( k \geq 4 \) and fix some \( n_0 \) such that \( |\omega_n| \geq s(k) \) whenever \( n \geq n_0 \). It then follows that

\[
\forall n \geq n_0, \quad p(\omega_k, \omega_n) = \sum_{\omega \in \mathcal{O}_{s(k)}} p(\omega_k, \omega)p(\omega, \omega_n) \geq \frac{1}{\binom{s(k)}{k}} \sum_{\omega \in \mathcal{O}_{s(k)}} p(\omega, \omega_n) = \frac{1}{\binom{s(k)}{k}}.
\]

The first identity is a standard conditional probability argument: instead of taking a random \( k \)-element subset of a realization of \( \omega_n \), we first take an \( s(k) \)-element subset, consider their order type \( \omega \), and then take a random \( k \)-element subset of a realization of \( \omega \) and estimate the probability that it has order type \( \omega_k \) conditioned on the order type of \( \omega \). The last identity simply expresses that the sum for all order types \( \omega \) of size \( s(k) \) of the density \( p(\omega, \omega_n) \) is 1. We derive that \( p(\omega_k, \omega_n) \geq \frac{1}{\binom{s(k)}{k}} \geq \frac{1}{2^{s(k)+1} \log k} \) for any \( n \geq n_0 \), so

\[
\ell(\omega_k) = \lim_{n \to \infty} p(\omega_k, \omega_n) \geq \frac{1}{2^{k^2 + o(k^2)}}.
\]

Our example \( \ell_E \) matches the order of growth in the exponent of Proposition 16. We don’t know of any previous result in this direction.
Proposition 17. $\ell_E(\phi_k) = 2^{-\frac{k^2}{4} + O(k \log k)}$.

Proof. Let $\mu$ be a measure that does not charge lines. Let $X$ and $S$ be two sets of random points chosen independently from $\mu$ of respective sizes $k$ and $\lfloor k/2 \rfloor$. By the discussion above,

$$\ell_\mu(\phi_k) = \mathbf{P}_\mu(X \text{ is in convex position}) \leq \binom{k}{\lfloor k/2 \rfloor} \mathbf{P}_\mu(S \text{ is a cup or a cap}).$$

Moreover, the construction of $\mu^{a,b}$ implies that

$$\mathbf{P}_{\mu^{a,b}}(S \text{ is a cup or a cap}) = 2 \mathbf{P}_{\mu^{a,b}}(S \text{ is a cup}).$$

The condition that $b \leq (1 - 2a)(1 - 2a)$ ensures that every $s$-cup containing more than one point in $\phi_0(R)$ contains at most one point in $\phi_1(R)$. It follows that

$$\mathbf{P}_{\mu^{a,b}}(S \text{ is a cup}) = \mathbf{P}_{\mu^{a,b}}(S \text{ is a cup and } S \subseteq \phi_0(R)) + \mathbf{P}_{\mu^{a,b}}(S \text{ is a cup and } S \subseteq \phi_1(R)) + \mathbf{P}_{\mu^{a,b}}(S \cap \phi_0(R) \text{ is a cup and } |S \cap \phi_0(R)| = |S| - 1)$$

Observe that

$$\mathbf{P}_{\mu^{a,b}}(S \text{ is a cup } | S \subseteq \phi_0(R)) = \mathbf{P}_{\mu^{a,b}}(S \text{ is a cup } | S \subseteq \phi_1(R)) = \mathbf{P}_{\mu^{a,b}}(S \text{ is a cup}).$$

Altogether, defining $f(s)$ to be the probability that $s$ random points chosen independently from $\mu^{a,b}$ form a cup, we have

$$f(s) = \frac{2}{2^s} f(s) + \frac{s}{2^s} f(s - 1),$$

that is, $f(s) = \frac{s}{2^s - 2} f(s - 1)$.

Notice that $f(3) = \frac{1}{2}$. This can be seen directly from the combinatorial description of $\ell_E$ as follows. Consider three different sequences $u, v, w \in \{0, 1\}^n$, assuming that $u \prec_{\text{lex}} v \prec_{\text{lex}} w$. The orientation of $(u, v, w)$ depends only on the first entry of $v$ where $u$ and $w$ differ, and this entry of $v$ is uniformly distributed in $\{0, 1\}$. Altogether,

$$f(s) = \prod_{i=3}^{s} \frac{i}{2^n - 2} = 2^{-\frac{s(s + 1)}{2} + 3} \prod_{i=3}^{s} \frac{i}{1 - 2^{-i+1}}$$

so $f(s) = 2^{-\frac{s^2}{4} + O(s \log s)}$ and $\ell_E(\phi_k) = 2^{-\frac{k^2}{4} + O(k \log k)}$. \hfill \square

Until recently it was suspected that every realization of the order types of Erdős-Szekeres needed to be very spread out, in the sense that the quotient of the diameter and the minimal distance between two points on every realization had to be exponentially large. A construction of the Erdős-Szekeres example in a grid of size polynomial in $n$ was recently achieved [15].

To some extent our next result vindicates the original intuition on realizations of the order types of Erdős-Szekeres. We show that the fast decay of $\ell_E(\phi_k)$ exhibited in Proposition 17 drastically restricts its space of realizations.

Lemma 3.16. Let $\mu$ be a finite measure over $\mathbb{R}^2$ for which lines are negligible and $U$ an open set of positive $\mu$-measure.

(i) If $\mu$ is absolutely continuous, on $U$, to the Lebesgue measure then $p(\phi_k, \mu) \geq 4^{-k \log k + O(k)}$.

(ii) If $\mu$ is absolutely continuous, on $U$, to the length measure on a $C^2$ curve then $p(\phi_k, \mu) \geq 2^{-O(k)}$.

Proof. By the Radon-Nikodym theorem [28, 29], if a measure $\mu$ is absolutely continuous to a measure $\lambda$ on a measurable set $X$ then there exists an absolutely continuous function $\frac{d\mu}{d\lambda}$ such that $\mu(A) = \int_A \frac{d\mu}{d\lambda} d\lambda$ for every measurable set $A \subseteq X$.

Let $\lambda_2$ be the Lebesgue measure over $\mathbb{R}^2$. Since $\mu(U) > 0$ and $\mu$ is absolutely continuous to $\lambda_2$ on $U$, the function $\frac{d\mu}{d\lambda_2}$ is nonnegative, nonzero, and continuous on $U$. In particular, $\mu$ contains some square $A$.  

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on which \( \frac{d\mu}{dx} \) is bounded from below by some positive constant \( c \). The probability that \( k \) random points chosen independently from \( \mu \) are all in \( A \) is \( \left( \frac{\mu(A)}{\mu(R^2)} \right)^k \). Conditioning on this event, we deduce that

\[
p(\gamma_k, \mu) \geq \left( \frac{\mu(A)}{\mu(R^2)} \right)^k \cdot p(\gamma_k, \mu_{|A}).
\]

Let \( 1_{\gamma_k} \) be the indicator function, over \( A^k \), of \( k \)-tuples of points in convex position. We have

\[
p(\gamma_k, \mu_{|A}) = \int_{A^k} 1_{\gamma_k} d\mu(x_1) d\mu(x_2) \ldots d\mu(x_k)
= \int_{A^k} 1_{\gamma_k} \frac{d\mu}{d\lambda_2} \frac{d\mu}{d\lambda_2} (x_1) \frac{d\mu}{d\lambda_2} (x_2) \ldots \frac{d\mu}{d\lambda_2} (x_k) d\lambda_2(x_1) d\lambda_2(x_2) \ldots d\lambda_2(x_k)
\geq c^k \int_{A^k} 1_{\gamma_k} d\lambda_2(x_1) d\lambda_2(x_2) \ldots d\lambda_2(x_k) = c^k p(\gamma_k, \lambda_{2|A})
\]

Valtr [39] proved that \( p(\gamma_k, \lambda_{2|A}) = \frac{1}{k^{2k-1}} \), so altogether

\[
p(\gamma_k, \mu) \geq \left( \frac{\mu(A)}{\mu(R^2)} \right)^k \cdot c^k \left( 2k - 1 \right)^2 = \Omega \left( 4^{-k \log k + O(k)} \right),
\]

which proves the first statement.

For the 1-dimensional case, let \( d\lambda_1 \) be the 1-dimensional Lebesgue measure and let \( \Gamma \) be a \( C^2 \) curve such that \( \mu \) is absolutely continuous to \( \lambda_1|_U \) on some open set \( U \). Since \( \frac{d\mu}{d\lambda_1} \) is continuous, nonnegative and nonzero, there is an open set \( U' \subseteq U \) such that \( \frac{d\mu}{d\lambda_1} \) is positive on \( \Gamma \cap U' \).

Since \( \Gamma \) is \( C^2 \), its curvature is a continuous function. As \( \mu \) does not charge lines, this curvature is nonzero and there exists an open subset \( U'' \subseteq U \) such that \( U'' \cap \Gamma \) is non-empty and \( \Gamma \) has positive curvature on \( U'' \). Up to passing to a smaller neighborhood, we can find an arc \( \gamma \) of our curve that has positive length and that is entirely on its convex hull. Hence, any \( k \) points on \( \gamma \) are in convex position. Moreover, \( \frac{d\mu}{d\lambda_1|_U} \) is positive on \( U'' \) and therefore on \( \gamma \), so \( \mu(\gamma) \) is positive. It follows that

\[
\forall k, \quad p(\gamma_k, \mu) \geq \left( \frac{\mu(\gamma)}{\mu(R^2)} \right)^k,
\]

which proves the second statement. \( \square \)

References


we use the following property coming from measure theory.

\[ \text{Then for every } \varepsilon > 0 \text{ and every measurable set } A \text{ there is } B \subseteq X \text{ such that } \mu(A \triangle B) \leq \varepsilon, \text{ where } \mu \text{ stands for the symmetric difference of } A \text{ and } B, \text{ that is } A \triangle B = (A \setminus B) \cup (B \setminus A). \]

**Proof.** One can prove the statement above by showing that the family of sets satisfying the property holds for the set \( A = \bigcup_{i \in \mathbb{N}} A_i \). For each \( i \in \mathbb{N} \), we know that there is a set \( B_i \subseteq X \) such that \( \mu(A_i \triangle B_i) \leq \varepsilon/2^i \). Taking \( S_k = \bigcup_{i=1}^{k} B_i \) for \( k \in \mathbb{N} \) and \( S_\infty = \bigcup_{i \in \mathbb{N}} B_i \), we have \( \mu(A \triangle S_\infty) \leq \sum_{i \in \mathbb{N}} \mu(A_i \triangle B_i) \leq 2\varepsilon. \) Note that \( (S_k)_{k \in \mathbb{N}} \) is an increasing sequence of sets of \( X \) whose union is \( S_\infty \). Since \( \mu \) is a probability measure, \( \mu(S_\infty) \) is finite. It follows that the real number sequence \( (\mu(S_k))_{k \in \mathbb{N}} \) tends to \( \mu(S_\infty) \) as \( k \) tends to infinity. Let \( k \in \mathbb{N} \) be an index such that \( \mu(S_k) - \mu(S_{k-1}) \leq \varepsilon \). Then \( \mu(S_\infty \triangle S_k) = \mu(S_\infty) - \mu(S_k) \leq \varepsilon \) because \( S_k \subseteq S_\infty \). It thus follows that \( \mu(A \triangle S_k) \leq \mu(A \triangle S_\infty) + \mu(S_\infty \triangle S_k) \leq 3\varepsilon. \)

**A Some elementary properties from measure theory**

In the proof of Lemma 3.10 we use the following property coming from measure theory.

**Lemma A.1.** If \((J, \mu)\) is a probability space and \( X \) is a non-empty family of measurable subsets of \( J \) such that

- \( X \) generates the \( \sigma \)-algebra of measurable sets; and
- \( X \) is stable under finite unions and complementary operations,

then for every \( \varepsilon > 0 \) and every measurable set \( A \subseteq X \) there is \( B \subseteq X \) such that \( \mu(A \triangle B) \leq \varepsilon \), where \( A \triangle B \) stands for the symmetric difference of \( A \) and \( B \), that is \( A \triangle B = (A \setminus B) \cup (B \setminus A) \).

**Proof.** One can prove the statement above by showing that the family of sets \( A \) for which there is indeed such an element \( B \subseteq X \) contains \( X \) and is stable under taking complements and countable unions.

The result is true if \( A \subseteq X \), since it then suffices to take \( B = A \). Assuming that \( A \) satisfies that \( \mu(A \triangle B) \leq \varepsilon \) for some \( B \subseteq X \), the complement \( A \setminus B \) of \( A \) in \( J \) also satisfies \( \mu(A \setminus B) = \mu(A \triangle B) \leq \varepsilon \) and \( B \) belongs to \( X \) since \( X \) is stable under taking complements. Let \( (A_i)_{i \in \mathbb{N}} \) be a countable family of measurable subsets satisfying the property and let us prove that the property holds for the set \( A = \bigcup_{i \in \mathbb{N}} A_i \). For each \( i \in \mathbb{N} \), we know that there is a set \( B_i \subseteq X \) such that \( \mu(A_i \triangle B_i) \leq \varepsilon/2^i \). Taking \( S_k = \bigcup_{i=1}^{k} B_i \) for \( k \in \mathbb{N} \) and \( S_\infty = \bigcup_{i \in \mathbb{N}} B_i \), we have \( \mu(A \triangle S_\infty) \leq \sum_{i \in \mathbb{N}} \mu(A_i \triangle B_i) \leq 2\varepsilon. \) Note that \( (S_k)_{k \in \mathbb{N}} \) is an increasing sequence of sets of \( X \) whose union is \( S_\infty \). Since \( \mu \) is a probability measure, \( \mu(S_\infty) \) is finite. It follows that the real number sequence \( (\mu(S_k))_{k \in \mathbb{N}} \) tends to \( \mu(S_\infty) \) as \( k \) tends to infinity. Let \( k \in \mathbb{N} \) be an index such that \( \mu(S_{k-1}) - \mu(S_k) \leq \varepsilon \). Then \( \mu(S_\infty \triangle S_k) = \mu(S_\infty) - \mu(S_k) \leq \varepsilon \) because \( S_k \subseteq S_\infty \). It thus follows that \( \mu(A \triangle S_k) \leq \mu(A \triangle S_\infty) + \mu(S_\infty \triangle S_k) \leq 3\varepsilon. \)
We focus on Borel measures of $\mathbb{R}^n$. In this case, the atoms are precisely the singletons with positive measure.

Lemma A.2 (Sikorski [34]). Let $\mu$ be an atom-free measure on a set $J$ and let $A \subseteq J$ be a measurable set with finite $\mu$-measure. Then for every every non-negative number $x \leq \mu(A)$, there is a measurable subset $B \subseteq A$ with $\mu(B) = x$.

Proof. If $y$ is a real number and $B_1, B_2 \subseteq J$ are measurable sets satisfying $\mu(B_1) \leq y \leq \mu(B_2)$, we define

$$\alpha(B_1, B_2, y) = \sup \{ \mu(X) \mid \mu(X) \leq y, B_1 \subseteq X \subseteq B_2 \}$$

where only measurable sets $X$ are considered.

We first prove that for every measurable set $B$ and real number $y$ such that $y \leq \mu(B) < \infty$, there exists a measurable set $C \subseteq B$ satisfying $\mu(C) = \alpha(C, B, y)$. To see this, we fix a sequence $(\varepsilon_n)_{n \in \mathbb{N}}$ of positive numbers tending to $0$. Next, we define an increasing sequence of sets $(C_n)_{n \in \mathbb{N}}$ satisfying $\mu(C_n) \leq y$ for every $n \in \mathbb{N}$ as follows. Set $C_0 = \emptyset$ and observe that by the definition of $\alpha$, for each $i \geq 1$, there exists a measurable set $C_i$ such that $C_{i-1} \subseteq C_i \subseteq B$ and $\mu(C_i) > \alpha(C_{i-1}, B, y) - \varepsilon_i$. Set $C = \bigcup_{n \in \mathbb{N}} C_n$ and note that $\alpha(C, B, y) \leq \alpha(C_n, B, y)$ since $C_n \subseteq C$ for every $n \in \mathbb{N}$. It follows that

$$\forall n \geq 1, \quad \mu(C_n) \geq \alpha(C_{n-1}, B, y) - \varepsilon_n \geq \alpha(C, B, y) - \varepsilon_n.$$

Letting $n$ tends to infinity yields that $\mu(C) \geq \alpha(C, B, y)$. This upper bound on the supremum $\alpha(C, B, y)$ is in particular reached by $C$, so $\mu(C) = \alpha(C, B, y)$. This proves the property stated.

Since $x \leq \mu(A) < \infty$, we thus know that there exists a measurable set $C_1 \subseteq A$ such that $\mu(C_1) = \alpha(C_1, A, x) \leq x$. Further, as $\mu(A) = x \leq \mu(A \setminus C_1) < \infty$, we also know that there exists a measurable set $C_2 \subseteq A \setminus C_1$ such that $\mu(C_2) = \alpha(C_2, A \setminus C_1, \mu(A) - x) \leq \mu(A) - x$.

As it turns out, the set $S = A \setminus (C_1 \cup C_2)$ is an atom unless it has measure 0. Indeed, suppose on the contrary that $S$ has a measurable subset $T$ with $0 < \mu(T) < \mu(S)$. Then $\mu(C_1 \cup T) > x$ since $\alpha(C_1, A, x) = \mu(C_1)$. Similarly, $\mu(C_2 \cup (S \setminus T)) > \mu(A) - x$ since $\alpha(C_2, A \setminus C_1, \mu(A) - x) = \mu(C_2)$. Consequently, on the one hand $\mu(A) < \mu(C_2 \cup (S \setminus T)) + \mu(C_1 \cup T)$ while on the other hand $A$ is the disjoint union of $(C_1 \cup T)$ and $(C_2 \cup (S \setminus T))$, which is a contradiction.

Therefore, since $\mu$ is atom-free, it follows that $\mu(S) = 0$, i.e., $\mu(A) = \mu(C_1) + \mu(C_2)$, which implies that $\mu(C_1) = x$. \qed