Common Fundamental Domains

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- Steinhaus (1950s): Are there $A, B \subseteq \mathbb{R}^2$ such that

$$|\tau A \cap B| = 1, \quad \text{for every rigid motion } \tau?$$

Are there two subsets of the plane which, no matter how moved, always intersect at exactly one point?

The classical Steinhaus question

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- Sierpiński, 1958:

Yes.

- Equivalent:

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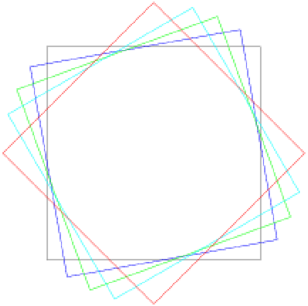
- In tiling language:

$$\rho A \oplus B = \mathbb{R}^2, \quad \text{for all rotations } \rho.$$

Every rotation of A tiles (partitions) the plane when translated at the locations B.

Fixing $B = \mathbb{Z}^2$: the lattice Steinhaus question

- Can we have $\rho A \oplus \mathbb{Z}^2 = \mathbb{R}^2$ for all rotations ρ?



Can a domain behave simultaneously like all those squares?

- Equivalent: A is a fundamental domain of all $\rho\mathbb{Z}^2$.
  Or,
  A tiles the plane by translations at any $\rho\mathbb{Z}^2$.

The lattice Steinhaus question

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  Sierpiński (1958), Croft (1982), Beck (1989),
  Mallinikova & Rukshin (1995), K. (1996):
  "Best" so far: (K. & Wolff (1999))
  If such a measurable A exists then it must be large at infinity:

$$\int_A |x|^{\frac{46}{27}+\epsilon}\, dx = \infty.$$

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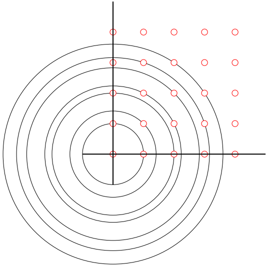
- In higher dimension:
  K. & Wolff (1999), K. & Papadimitrakis (2002):
  No measurable Steinhaus sets exist for $\mathbb{Z}^d$, $d \geq 3$.
  No Jackson - Mauldin analogue is known for $d \geq 3$.

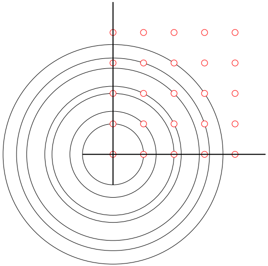
- For A to have the Steinhaus property it is equivalent



that $\widehat{\mathbf{1}_A}$ must vanish on all circles through lattice points.

The zeros of the Fourier Transform

- For A to have the Steinhaus property it is equivalent



  that $\widehat{\mathbf{1}_A}$ must vanish on all circles through lattice points.

- Too many zeros imply strong decay of $\widehat{\mathbf{1}_A}$ near infinity.

  This implies continuity, but $\mathbf{1}_A$ is an indicator function.

Lattice Steinhaus for finitely many lattices

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  can we find measurable A which tiles with all Λ_j?

Lattice Steinhaus for finitely many lattices

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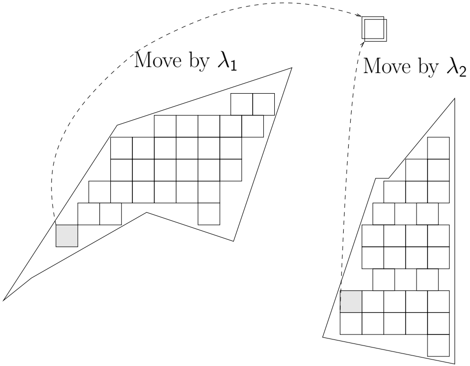
Generically yes!

- If the sum $\Lambda_1^* + \cdots + \Lambda_n^*$ is direct then Kronecker-type density theorems allow us to rearrange a fundamental domain of one lattice to accommodate the others.



An application in Gabor analysis

- If K, L are two lattices in $\mathbb{R}^d$ with

$$\mathrm{vol}\, K \cdot \mathrm{vol}\, L = 1,$$

can we find $g \in L^2(\mathbb{R}^d)$, such that the (K, L) time-frequency translates

$$g(x-k)e^{2\pi i \ell \cdot x}, \quad (k \in K, \ell \in L)$$

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- Han and Wang (2000):
Since $\mathrm{vol}\,(L^*) = \mathrm{vol}\,(K)$ let $g = \mathbf{1}_E$ where
E is a **common tile** for K, L^*.
- L forms an orthogonal basis for any FD of L^*, so of $L^2(E+x)$ (for any x).
- Space partitioned in K-translates of E and on each copy L is an orthogonal basis.

Multi-tiling functions

- A function f tiles with the set of translates Λ if

$$\sum_{\lambda \in \Lambda} f(x - \lambda) = \text{const.} \quad \text{a.e. } x \in \mathbb{R}^d.$$

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- We can find a common tiling function f for any set of lattices

$$\Lambda_1, \ldots, \Lambda_N \subseteq \mathbb{R}^d.$$

Just take (the D_j are fundamental domains of Λ_j)

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- For such an f if $\operatorname{vol} \Lambda_j \gtrsim 1$ then

$$\operatorname{diam} \operatorname{supp} f \gtrsim N.$$

Multi-tiling functions: diameter lower bounds

- (K. and Wolff, 1997): If $f \in L^1(\mathbb{R}^d)$, with $\int f \neq 0$, tiles $\mathbb{R}^d$ with $\Lambda_1, \ldots, \Lambda_N$, and

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QUESTION

What is the smallest $\operatorname{diam} \operatorname{supp} f$?

We know

$$N^{1/d} \lesssim \operatorname{diam} \operatorname{supp} f \lesssim N.$$

at least when $\Lambda_i \cap \Lambda_j = \{0\}$.

Multi-tiling functions: a case of large diameter

Take $\alpha_1, \ldots, \alpha_N \in (\frac{1}{2}, 1)$ to be $\mathbb{Q}$-linearly independent and

$$\Lambda_j = \mathbb{Z}(\alpha_j, 0) + \mathbb{Z}(0, \alpha_j^{-1}), \quad \Lambda_j^* = \mathbb{Z}(\alpha_j^{-1}, 0) + \mathbb{Z}(0, \alpha_j).$$

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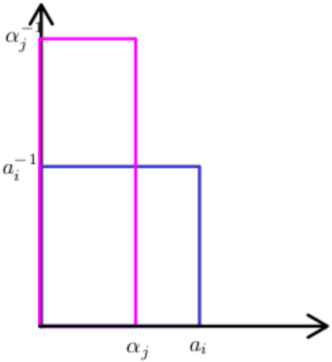
f tiles with all $\Lambda_j \implies \widehat{f} \equiv 0$ on Λ_j^*.

$\widehat{f}$ has zeros of density $\gtrsim N$ along the axes. So

$$\operatorname{diam} \operatorname{supp} f \gtrsim N.$$

(K. & Papageorgiou, 2022)



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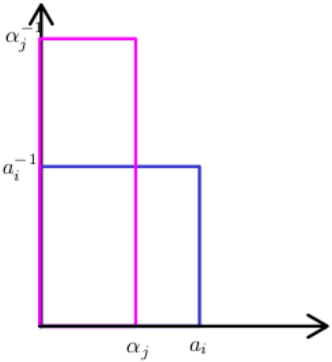
Generic over $\mathbb{Q}$ (no algebraic relations) but not geometrically generic (alignment).



Multi-tiling functions: a case of large diameter

Question

Is there any case of "generic" lattices with a common tile f s.t.

$$\operatorname{diam}\operatorname{supp} f = o(N)?$$

Multi-tiling functions: the volume of the support

- If $f = \mathbf{1}_{D_1} * \cdots * \mathbf{1}_{D_N}$ or (more generally)

$$f = f_1 * \cdots * f_N, \quad \text{where } f_j \ge 0 \text{ tiles with } \Lambda_j \tag{1}$$

then

$$\operatorname{supp} f = \operatorname{supp} f_1 + \cdots + \operatorname{supp} f_N$$

and (Brunn - Minkowski inequality)

$$|\operatorname{supp} f| \ge \left(|\operatorname{supp} f_1|^{1/d} + \cdots + |\operatorname{supp} f_N|^{1/d} \right)^d \gtrsim N^d.$$

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Question

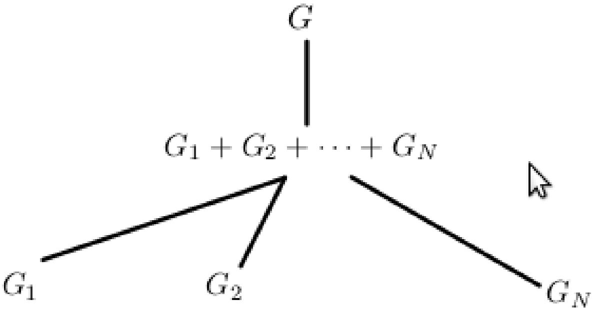
What if we drop nonnegativity from (1)?

What if f is *any* common tile of the Λ_j, not given by (1)?

Multi-tiling sets: Giving up measurability

- If $G_1, \ldots, G_N$ are subgroups of G it is always enough to find a common fundamental domain (a common tile) of the G_j in

$$G_1 + \cdots + G_N.$$



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- (K. 1997) If the lattices $\Lambda_1, \ldots, \Lambda_N$ in $\mathbb{R}^d$ have
  (a) *the same volume* and
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- A common FD for the lattices $\Lambda_i = \left\{\lambda_j^i\right\}_{j\in\mathbb{N}}$ in the group $\Lambda_1 + \cdots + \Lambda_N$ is

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- Hall's "marriage" theorem $\Longrightarrow$ a good lattice enumeration.

Theorem

If $\mathrm{vol}\,\Lambda_i = \mathrm{vol}\,\Lambda_j$ *then there is a bijection* $f_{ij} : \Lambda_i \to \Lambda_j$ *with*

$$|x - f(x)| \ \textit{bounded.}$$

Equal lattice density necessary for boundedness

Theorem (S. Grepstad, M.K. & M. Spyridakis (2025))

Assume that L, M are two-full rank lattices in $\mathbb{R}^d$, with

$$\mathrm{vol}\,(L) < \mathrm{vol}\,(M)$$

such that

$$L \cap M = \{0\}.$$

Furthermore assume that F is a common fundamental domain of L, M in $\mathbb{R}^d$. Then F is unbounded.

No measurability of the FD assumed.

Proof for $d = 1$

- Assume $\Lambda_1 = \mathbb{Z}$ and $\Lambda_2 = \alpha\mathbb{Z}$, with $\alpha > 1$, irrational.
- If F is a bounded FD in $G = \Lambda_1 + \Lambda_2 = \{m + n\alpha : \ m, n \in \mathbb{Z}\}$:

$$F = m_i - n_i\alpha : i = 1, 2, \ldots \subseteq [-M, M].$$

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  Renumbering: $F = \{m - n_m\alpha : m \in \mathbb{Z}\}$.
- Restricting $-R \leq m \leq R$ we get

$$|m - n_m\alpha| \leq M.$$

or

$$-\frac{R+M}{\alpha} \leq n_m \leq \frac{R+M}{\alpha}.$$

- $\sim 2R$ values of m correspond to only $\sim \frac{2}{\alpha}R$ values of n_m
  Contradiction, as all n_m must be different
  ($d = 1$: K. & Papageorgiou, 2022, $d \geq 2$: Grepstad, K. & Spyridakis, 2025).

Lattice Steinhaus for finitely many lattices

Question

Is there a *measurable, bounded* common tile for $\Lambda_1, \ldots, \Lambda_N$?

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Theorem (S. Grepstad and M.K. (2025))

If L, M are lattices in $\mathbb{R}^d$ of the same volume then they possess a ***bounded****,* ***measurable*** *common fundamental domain.*

Tile with a lattice, pack with another

Theorem (S. Grepstad, M.K. & M. Spyridakis (2025))

If L, M are lattices in $\mathbb{R}^d$ with $\mathrm{vol}\, M > \mathrm{vol}\, L$ then there exists a bounded $E \subseteq \mathbb{R}^d$ such that E tiles with L and E packs with M.

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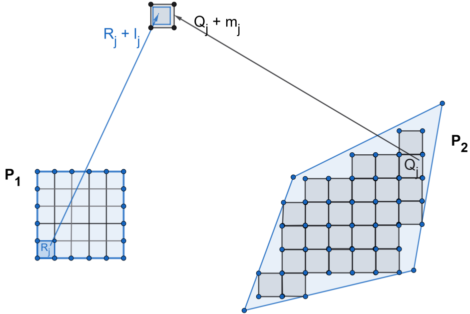
- Not reducible to common fundamental domains.
- Is actually much easier than the common fundamental domain: larger volume allows room to work.



Tiling finite abelian groups with a function

- G_1, G_2 subgroups of G, $f : G \to \mathbb{R}^{\geq 0}$ s.t.

$$\forall x \in G : \quad \sum_{g_1 \in G_1} f(x - g_1) = |G_1|, \qquad \sum_{g_2 \in G_2} f(x - g_2) = |G_2|.$$

For example $f(x) \equiv 1$.

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Question

How small can $|\mathrm{supp}\, f|$ be?

- Write

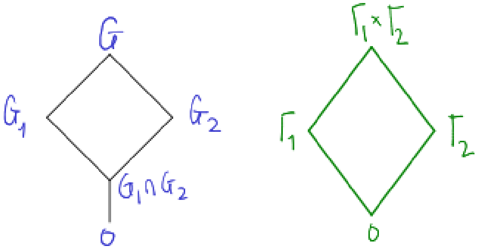
$$S^G_{G_1,G_2} = \min \{|\mathrm{supp}\, f| : \; f * \mathbf{1}_{G_1} \equiv |G_1| \mathbf{1}_G, \; f * \mathbf{1}_{G_2} \equiv |G_2| \mathbf{1}_G\}.$$

- Always $S^G_{G_1,G_2} \geq \max\{[G : G_1], [G : G_2]\}$.

Reduction to product groups

- If $\Gamma = G/(G_1 \cap G_2)$, $\Gamma_i = G_i/(G_1 \cap G_2)$ then

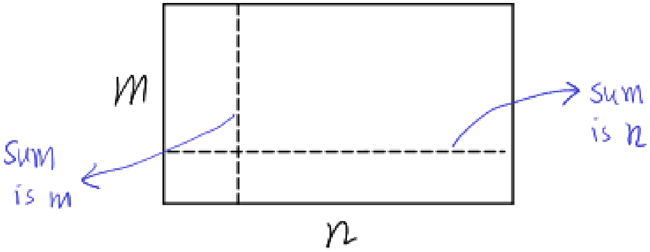
$$S^{G}_{G_1,G_2} = S^{\Gamma}_{\Gamma_1,\Gamma_2}. \tag{2}$$



- Can assume: $G = G_1 \times G_2$.

The problem in matrix form

- Group structure irrelevant.



- Find $m \times n$ matrix A with
  row sums equal to n, column sums equal to m.
- Minimize the support. Call $S(m, n)$ the minumum.

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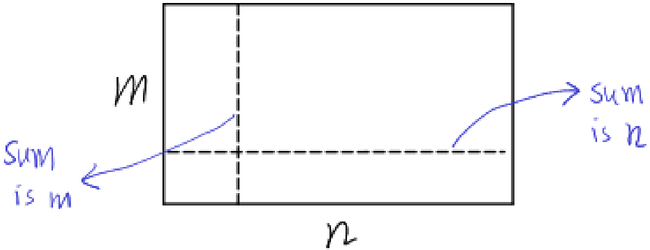


- Find $m \times n$ matrix A with
  row sums equal to n, column sums equal to m.
- Minimize the support. Call $S(m, n)$ the minumum.
- Statisticians call these *copulas* and use them a lot.
  A generalization of doubly stochastic matrices.

The case m divides n

$$\underbrace{m\left\{\begin{bmatrix} \overbrace{m\cdots m}^{k} & \cdots & \cdots \\ \cdots & \overbrace{m\cdots m}^{k} & \cdots \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \overbrace{m\cdots m}^{k} \end{bmatrix}\right.}_{km}$$

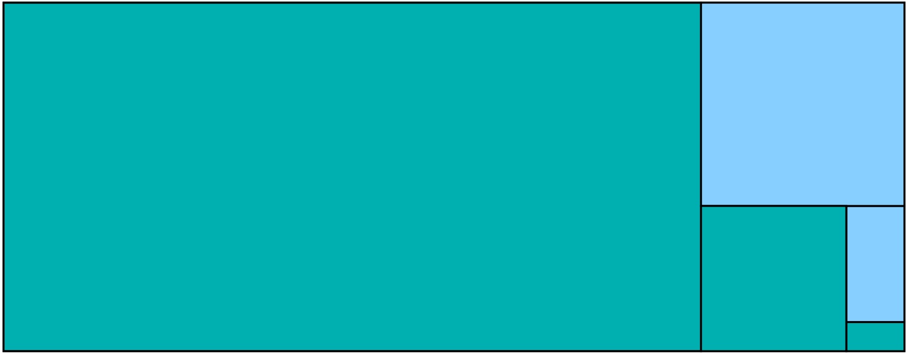
- Smallest possible support, since we must have ≥ 1 element/column.

$$S(km, m) = km.$$

The general case: Loukaki, 2022, Etkind and Lev, 2022

Theorem

$S(m, n) = m + n - \gcd(m, n)$



Tiling $\mathbb{R}$ with two lattices: a lower bound for the length

- Suppose $f : \mathbb{R} \to \mathbb{R}^{\geq 0}$ is measurable and tiles with both $\Lambda_1 = \mathbb{Z}$ and with $\Lambda_2 = \alpha\mathbb{Z}$, where $\alpha \in (0, 1)$:

$$\sum_{n \in \mathbb{Z}} f(x - n) = 1, \quad \sum_{n \in \mathbb{Z}} f(x - n\alpha) = \frac{1}{\alpha}, \quad \text{for almost every } x \in \mathbb{R}. \tag{3}$$

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Then

$$|\mathrm{supp}\, f| \geq \left\lceil \frac{1}{\alpha} \right\rceil \alpha \geq 2\alpha. \tag{4}$$

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- When $\alpha = 1 - \epsilon$: convolution $\mathbf{1}_{[0,1]} * \mathbf{1}_{[0,\alpha]}$ is almost optimal.
- When $\alpha = \frac{1}{2} + \epsilon$ there is a big gap $1 + 2\epsilon$ to $3/2 + \epsilon$.

Question

What is the smallest possible length of $\operatorname{supp} f$ which tiles with $\mathbb{Z}$ and $\alpha\mathbb{Z}$?

Tiling $\mathbb{R}$ with two lattices: Etkind and Lev, 2022

$\sum_{k\in\mathbb{Z}} f(x-k\alpha)=p, \quad \sum_{k\in\mathbb{Z}} f(x-k\beta)=q$. What about the measure of $\mathrm{supp}\, f$?

- $\alpha/\beta \notin \mathbb{Q}$
  - For all $p, q \in \mathbb{C}$ there is measurable f with $|\mathrm{supp}\, f| \le \alpha+\beta$
  - If $p/q \notin \mathbb{Q}^+$ then for any f must have $|\mathrm{supp}\, f| \ge \alpha+\beta$.
  - If $f \ge 0$ or $f \in L^1$ or f has bounded support then $p/q=\beta/\alpha$, $|suppf| \ge \alpha+\beta$.
  - If $p/q \in \mathbb{Q}^+$, $\gcd(p,q)=1$ we can have

$$|\mathrm{supp}\, f| < \alpha+\beta-\min\left\{\frac{\alpha}{q},\frac{\beta}{p}\right\}+\epsilon$$

    and must have

$$|\mathrm{supp}\, f| > \alpha+\beta-\min\left\{\frac{\alpha}{q},\frac{\beta}{p}\right\}$$

- $\alpha/\beta \in \mathbb{Q}^+$ and simplifying to $\alpha=n, \beta=m$, with $\gcd(n,m)=1$.

  Then $p/q=m/n$ and the least possible $|\mathrm{supp}\, f|$ is $n+m-1$.

3 subgroups in a finite abelian group: Aivazidis, Loukaki and Sambale, 2023

- If $A_1, \ldots, A_t$ are *complemented* isomorphic subgroups of G and the smallest prime divisor of $|A_1|$ is $\geq t$ then they have a common complement in G.

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  $A \subseteq G$ is *complemented* if some FD of A in G is a subgroup of G (called *complement* of A).
- If $A, B, C \subseteq G$ are cyclic groups of same order then they have a commond FD in G if and only if the following does not hold:
  $|A| = |B| = |C|$ is even and the product of their 2-Sylow subgroups $A_2B_2C_2$ satisifies
  $$A_2B_2C_2/I = A_2/I \times B_2/I = A_2/I \times C_2/I = B_2/I \times C_2/I$$
  where $I = A_2 \cap B_2 \cap C_2$.

Diameter: lattices with many relations

- **Main observation:** $\Lambda_1, \ldots, \Lambda_N \supseteq \Lambda$ and D is a FD of Λ then

$$f = \mathbf{1}_D \text{ tiles with all } \Lambda_i \text{ at level } [\Lambda_i : \Lambda].$$

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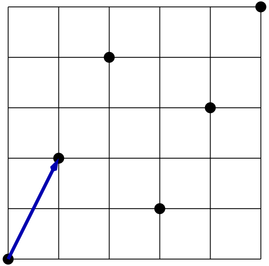
- Let G be a subgroup of $\mathbb{Z}_p^d$. Define the lattice $\Lambda_G = (p\mathbb{Z})^d + G$, which contains $\Lambda = (p\mathbb{Z})^2$ with FD

$$[0, p)^d \text{ of diameter } \sqrt{d}p.$$

- Restrict to cyclic subgroups G of $\mathbb{Z}_p^d$:



Back to the diameter: an example, continued

- There are
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- $f(x) := \mathbf{1}_{[0,p)^d}(N^{1/d}x) = \mathbf{1}_{[0,N^{-1/d}p]^d}(x)$ is a common tile for the Λ'_G of diameter
$$\sqrt{d}p \cdot N^{-1/d} = \sqrt{d} N^{\frac{1}{d-1}} N^{-\frac{1}{d}} = \sqrt{d}\, N^{\frac{1}{d(d-1)}} \quad \text{(much less than } N^{1/d}\text{)}.$$

(K. & Papageorgiou, 2022)

Question

Derive a lower bound, growing with N, for

$$\operatorname{diam} \operatorname{supp} f$$

where

$$f \text{ tiles with } \Lambda_1, \ldots, \Lambda_N$$

and $\operatorname{vol} \Lambda_j = 1$.

Diameter: The case $d = 1$.

- Previous construction gives nothing in dimension $d = 1$.

Theorem

We can find N lattices $\Lambda_j \subseteq \mathbb{R}$ of with $\mathrm{vol}\,\Lambda_j \sim 1$ and a function f with $\int f > 0$ and supported in an interval of length

$$\frac{N}{\log^{0.086\cdots} N}$$

which tiles with all Λ_j.

For any $\epsilon > 0$ any such function f must have

$$\mathrm{diam}\,\mathrm{supp}\, f \gtrsim_\epsilon N^{1-\epsilon}.$$

(K. & Papageorgiou, 2022)

Diameter: The case $d = 1$, continued

- Define
$$\Lambda_j = \lambda_j \mathbb{Z} = \frac{1}{N+j}\mathbb{Z}, \quad j = 1, 2, \ldots, N.$$
Then
$$\Lambda_j^* = (N+j)\mathbb{Z},$$
with union $U = \bigcup_{j=1}^{N} (N+j)\mathbb{Z}$.
- f tiles with all $\Lambda_j \iff \widehat{f}$ vanishes on $U \setminus \{0\}$.

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- *Erdős, 1935*: The integers divisible by one of $N+1, N+2, \ldots, 2N$ have density $\to 0$ as $N \to \infty$.
- *Tenenbaum, 1980*: Their density is
$$O\left(\frac{1}{\log^{0.086\cdots} N}\right).$$

Diameter: The case $d = 1$, continued

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- *Beurling*: U separated, $\mathrm{dens}\, U < \rho \implies$

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- With $\rho = O\left(\frac{1}{\log^{0.086\cdots} N}\right)$ we get a common tile f of support $o(1)$.
- Scale up by a factor of N:

$$f'(x) = f(x/N), \quad \operatorname{diam} \operatorname{supp} f' = o(N),$$

$$\Lambda_j' = N\Lambda_j = \frac{N}{N+j}\mathbb{Z} \text{ have vol} \sim 1.$$

Diameter: The case $d = 1$: lower bounds

- f tiles with $\Lambda_1, \ldots, \Lambda_N$, $\mathrm{dens}\,\Lambda_j \sim 1$, $\implies$

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- *Jensen's formula*: Since $\widehat{f}$ has $\gtrsim N^{2-\epsilon}$ roots in $[-N, N]$ $\implies$

$$\mathrm{diam}\,\mathrm{supp}\, f \gtrsim N^{1-\epsilon}.$$

The end

Thank you for your attention!