Sparse high-dimensional FFT using rank-1 lattices

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joint work with Lutz Kämmerer and Daniel Potts

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EFRE
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- torus $\mathbb{T} \simeq [0,1)$, Hilbert space $L_2(\mathbb{T})$
- trigonometric monomials $\mathrm{e}^{2\pi \mathrm{i} k x}$, $k \in \mathbb{Z}$, orthonormal basis of $L_2(\mathbb{T})$
- function $f \in L_2(\mathbb{T})$, $f(x) = \sum_{k\in\mathbb{Z}} \hat{f}_k \, \mathrm{e}^{2\pi \mathrm{i} k x}, \quad \hat{f}_k \in \mathbb{C}$
- smooth function $f \implies$ fast decay of Fourier coefficients $\hat{f}_k$
- truncated Fourier series $S_I f(x) = \sum_{k\in I} \hat{f}_k \, \mathrm{e}^{2\pi \mathrm{i} k x} \approx f(x)$
- $\hat{f}_k = \int_{\mathbb{T}} f(x) \, \mathrm{e}^{-2\pi \mathrm{i} k x} \, \mathrm{d}x \approx \tilde{\hat{f}}_k := \frac{1}{2N} \sum_{j=0}^{2N-1} f(x_j) \, \mathrm{e}^{-2\pi \mathrm{i} k x}$, $x_j := \frac{j}{2N}$
- various applications

$\Rightarrow$ transfer to multivariate case

$$(\tilde{\hat{f}}_k)_{k\in I} \xleftrightarrow[\text{FFT}]{\text{1-dim.}} (f(x_j))_{j=0}^{2N-1}$$

$\mathcal{O}(N \log N)$

[Gauß 1866] [Cooley, Tukey 1965]

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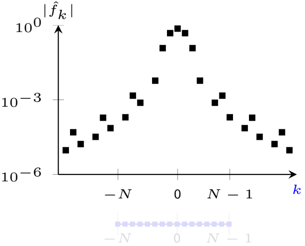

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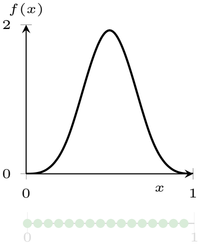

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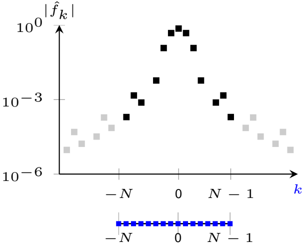

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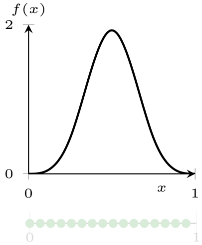

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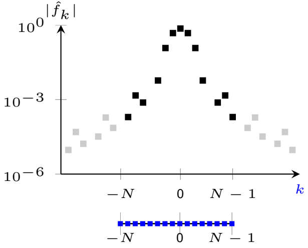

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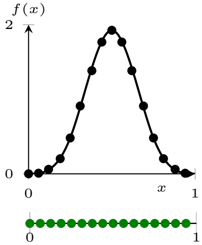

Approximation of periodic functions

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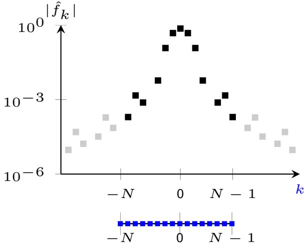

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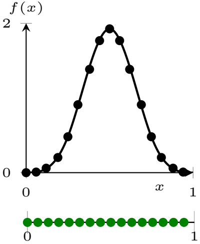
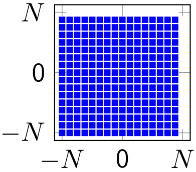


- full grid in frequency domain, equispaced grid in spatial domain



$$(\hat{\tilde{\tilde{f}}}_{\boldsymbol{k}})_{\boldsymbol{k}\in I} \xleftrightarrow[\text{FFT}]{d\text{-dim.}} (f(\boldsymbol{x}_j))_{j=0}^{|I|-1}$$

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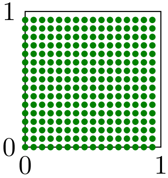
curse of dimensionality



? high-dimensional case $\Longrightarrow$ assumption: sparsity or smoothness

- hyperbolic cross in frequency domain, sparse grid in spatial domain

[Smolyak '63; Temlyakov '85; Baszenski, Delvos '89; Hallatschek '92; Gradinaru '07; Griebel, Hamaekers '14]

$$(\hat{\tilde{\tilde{f}}}_{\boldsymbol{k}})_{\boldsymbol{k}\in I} \xleftrightarrow[\text{HCFFT}]{} (f(\boldsymbol{x}_j))_{j=0}^{|I|-1}$$

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condition number of Fourier matrix
[Kämmerer, Kunis '11]

? more general frequency index set $I \subset \mathbb{Z}^d$, $|I| < \infty$; different sampling set

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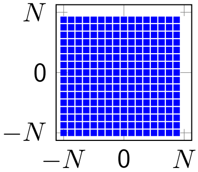

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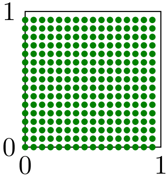

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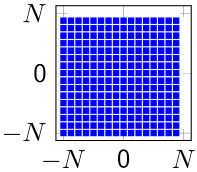

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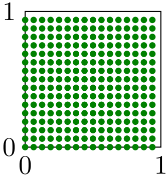

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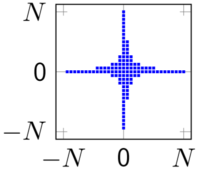

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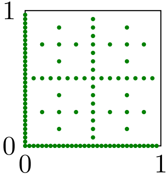

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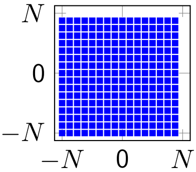

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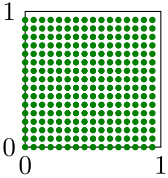

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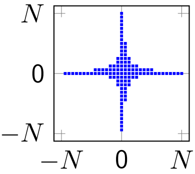

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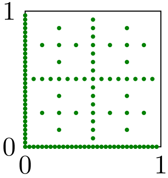

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Outline

1. Introduction

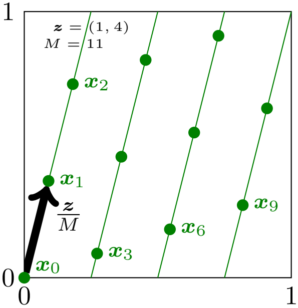
2. Fast reconstruction and approximation of multivariate periodic functions using rank-1 lattice sampling

3. High-dimensional dimension-incremental sparse FFT

4. High-dimensional sparse FFT and multiple rank-1 lattices

5. Conclusion

- $f(\boldsymbol{x}) = p_I(\boldsymbol{x}) = \sum_{\boldsymbol{k}\in I} \hat{p}_{\boldsymbol{k}} \, \mathrm{e}^{2\pi\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}}$, arbitrary index set $I \subset \mathbb{Z}^d$, $|I| < \infty$
- rank-1 lattice $\mathrm{R1L}(\boldsymbol{z}, M) := \{\boldsymbol{x}_j := \frac{j}{M}\boldsymbol{z} \bmod \boldsymbol{1}\}_{j=0}^{M-1}$, $\boldsymbol{z} \in \mathbb{Z}^d$, $M \in \mathbb{N}$, as discretization in spatial domain



Korobov '59
Maisonneuve '72
Sloan & Kachoyan '84,'87,'90
Temlyakov '86
Lyness '89
Sloan & Joe '94
Sloan & Reztsov '01
Li & Hickernell '03
Kämmerer & Kunis & Potts '12

$$\hat{p}_{\boldsymbol{0}} = \int_{\mathbb{T}^d} p_I(\boldsymbol{x}) \, \mathrm{d}\boldsymbol{x} \approx \sum_{j=0}^{M-1} \frac{1}{M} \, p_I(\boldsymbol{x}_j)$$

$$\hat{p}_{\boldsymbol{k}} = \int_{\mathbb{T}^d} p_I(\boldsymbol{x}) \, \mathrm{e}^{-2\pi\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}} \, \mathrm{d}\boldsymbol{x}, \quad \boldsymbol{k} \in I$$

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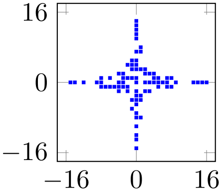
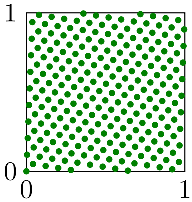


$$(\hat{p}_{\boldsymbol{k}})_{\boldsymbol{k}\in I} \overset{?}{\longleftarrow} (p_I(\boldsymbol{x}_j))_{j=0}^{M-1}$$

$$\mathcal{O}(M \log M + d\,|I|)$$



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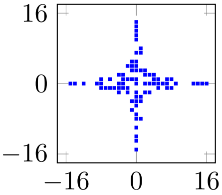
$\Rightarrow$ reconstructing $\mathrm{R1L}(\boldsymbol{z}, M, I)$ for given frequency index set I:
$\boldsymbol{k}\cdot\boldsymbol{z} \not\equiv \boldsymbol{k}'\cdot\boldsymbol{z} \pmod M$ for all $\boldsymbol{k}, \boldsymbol{k}' \in I$, $\boldsymbol{k} \neq \boldsymbol{k}'$ [Kämmerer,Kunis,Potts '12]

  - $|I| \le M \le |I|^2$, simple CBC construction method [Kämmerer '12]
  - $\hat{g}_l := \frac{1}{M} \sum_{j=0}^{M-1} p_I(\boldsymbol{x}_j)\, \mathrm{e}^{-2\pi\mathrm{i}jl/M}$, $l = 0, \ldots, M-1$; $\hat{p}_{\boldsymbol{k}} = \hat{g}_{\boldsymbol{k}\cdot\boldsymbol{z} \bmod M}$, $\boldsymbol{k} \in I$



$(\hat{p}_{\boldsymbol{k}})_{\boldsymbol{k}\in I} \xleftarrow[\text{FFT}]{\text{1-dim.}} (p_I(\boldsymbol{x}_j))_{j=0}^{M-1}$

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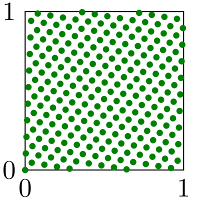

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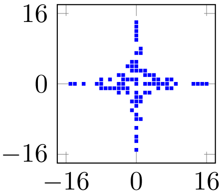
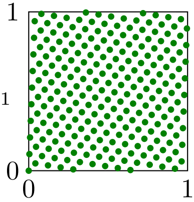
- fast approximation of $f \in L_2(\mathbb{T}^d) \cap C(\mathbb{T}^d)$, [Byrenheid,Kämmerer,Ullrich,V. '16] [V. '17]
  $f(\boldsymbol{x}) = \sum_{\boldsymbol{k}\in\mathbb{Z}^d} \hat{f}_{\boldsymbol{k}}\, \mathrm{e}^{2\pi\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}}$, by $S_I^{\mathrm{R1L}} f(\boldsymbol{x}) = \sum_{\boldsymbol{k}\in I} \hat{f}_{\boldsymbol{k}}^{\mathrm{R1L}}\, \mathrm{e}^{2\pi\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}}$



$$(\hat{f}_{\boldsymbol{k}}^{\mathrm{R1L}})_{\boldsymbol{k}\in I} \xleftarrow[\text{FFT}]{\text{1-dim.}} (f(\boldsymbol{x}_j))_{j=0}^{M-1}$$

$$\mathcal{O}(M \log M + d\,|I|)$$



until now:

- fast reconstruction / approximation from samples
  for arbitrary given frequency index set $I \subset \mathbb{Z}^d$, $|I| < \infty$

next: unknown frequency index set $I \Rightarrow$ multi-dimensional sparse FFT

- task: Determine frequency index set I from samples
  belonging to ≈largest Fourier coefficients $\hat{f}_{\boldsymbol{k}}$ or to $\hat{f}_{\boldsymbol{k}} \neq 0$
- search domain $\Gamma \subset \mathbb{Z}^d$, e.g. full grid $\hat{G}_N^d := \{-N, -N+1, \ldots, N\}^d$, $N \in \mathbb{N}$
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  - Chinese Remainder Theorem [Cuyt, Lee '08] [Iwen '13]
  - Prony's method [Tasche, Potts '13] [Peter, Plonka, Schaback '15]
    [Kunis, Peter, Römer, von der Ohe '15]
- problems: non-sparsity, implementations?, stability, many frequencies

$\Rightarrow$ dimension-incremental sparse FFT based on rank-1 lattices [Potts, V. '15] [V. '17]
(similar basic idea without rank-1 lattices:
[Zippel '79] [Kaltofen, Lee '03] [Javadi Monagan '10] [Potts, Tasche '13])

Unknown frequency index set I

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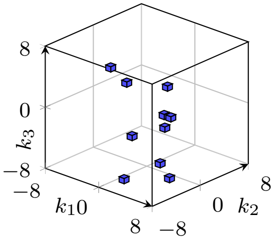


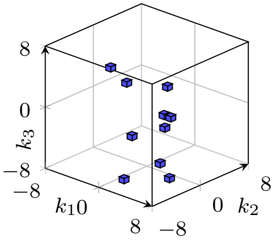
$I \subset \Gamma = \hat{G}_8^3$

$$\hat{p}_{k_1} := \frac{1}{17} \sum_{\ell=0}^{16} p\left(\begin{pmatrix} \ell/17 \\ x_2' \\ x_3' \end{pmatrix}\right) \mathrm{e}^{-2\pi\mathrm{i}\frac{\ell k_1}{17}}$$

$k_1 = -8, \ldots, 8$

frequency candidates

sampling nodes $\{(\frac{\ell}{17}, x_2', x_3')\}_{\ell=0}^{16}$



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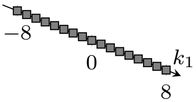

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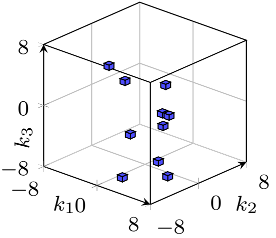

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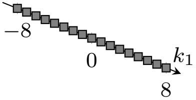
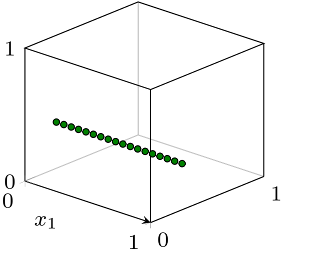
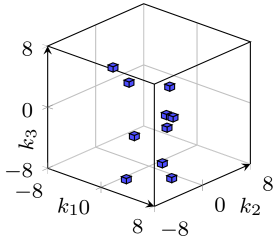


frequency candidates

construct $\longrightarrow$ sampling set



sampling nodes $\{(\frac{\ell}{17}, x_2', x_3')\}_{\ell=0}^{16}$



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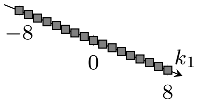
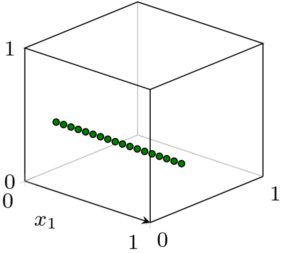
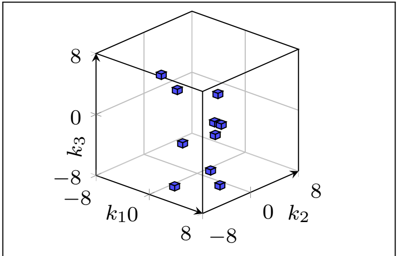


frequency candidates

1-dim. $\longleftarrow$ FFT



sampling nodes $\{(\frac{\ell}{17}, x_2', x_3')\}_{\ell=0}^{16}$



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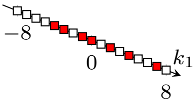
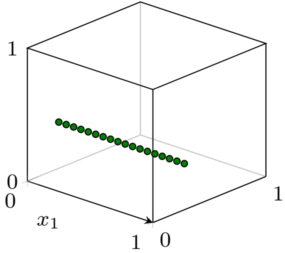
$$= \sum_{\substack{(h_2,h_3)\in\{-8,\ldots,8\}^2\\ (k_1,h_2,h_3)^\top\in\operatorname{supp}\hat{p}}} \hat{p}_{\begin{pmatrix}k_1\\ h_2\\ h_3\end{pmatrix}} \mathrm{e}^{2\pi\mathrm{i}(h_2x_2'+h_3x_3')},$$

$k_1 = -8, \ldots, 8$



detected frequencies $I^{(1)}$

1-dim. $\longleftarrow$ FFT



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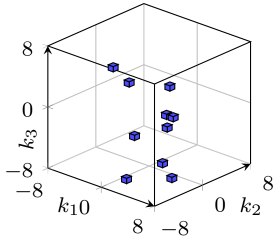

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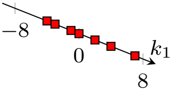
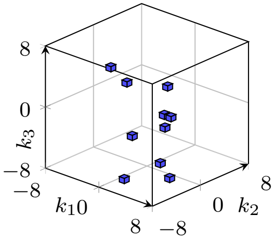


detected frequencies
$I^{(1)}$

frequency candidates

sampling nodes



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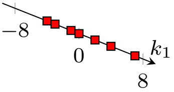
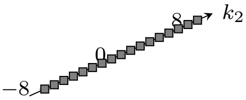
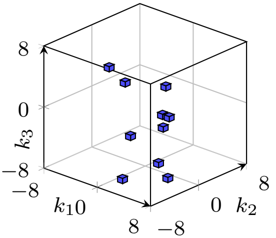


detected frequencies
$I^{(1)}$



frequency candidates

sampling nodes



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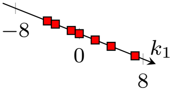
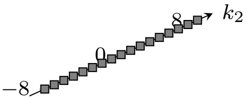
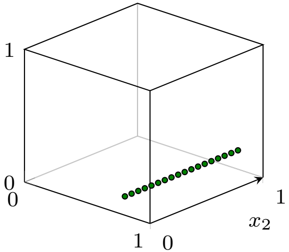


detected frequencies
$I^{(1)}$

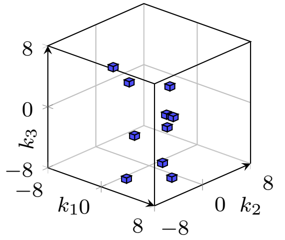


frequency candidates

construct
$\longrightarrow$
sampling set



sampling nodes



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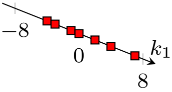
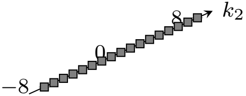
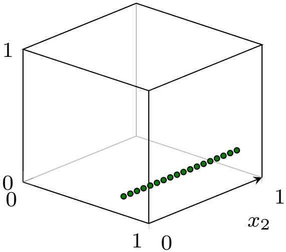


detected frequencies $I^{(1)}$



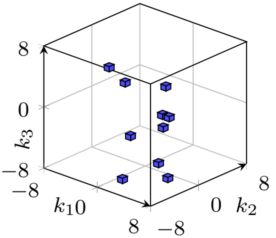
frequency candidates

1-dim. FFT ⟵

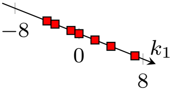


sampling nodes

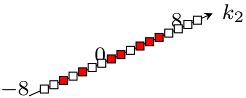
High-dimensional dimension-incremental sparse FFT [Potts, V. '15] [V. '17]
Method



$I \subset \Gamma = \hat{G}_8^3$

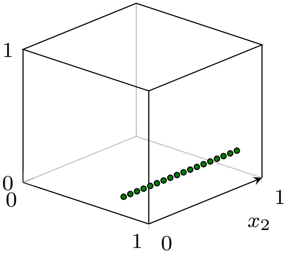


detected frequencies $I^{(1)}$

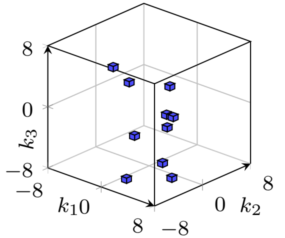


detected frequencies $I^{(2)}$

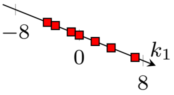
1-dim.
⟵
FFT



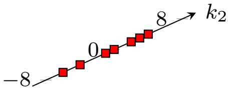
sampling nodes



$I \subset \Gamma = \hat{G}_8^3$

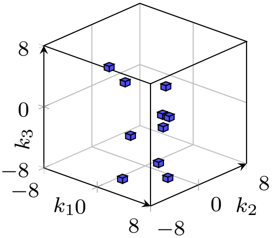


detected frequencies $I^{(1)}$



detected frequencies $I^{(2)}$

frequency candidates $I^{(1)} \times I^{(2)}$



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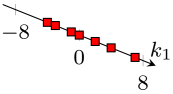
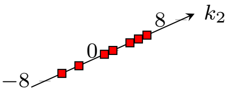
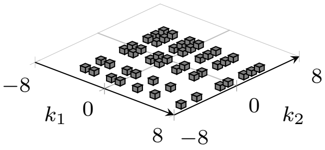


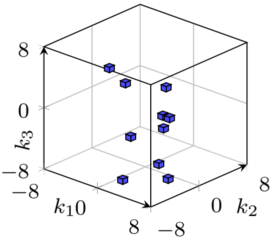
detected frequencies
$I^{(1)}$



detected frequencies
$I^{(2)}$



frequency candidates $I^{(1)} \times I^{(2)}$



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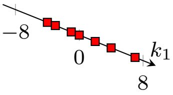
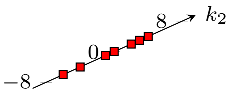
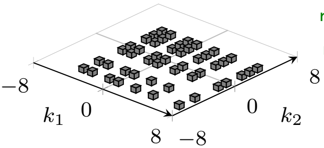


detected frequencies $I^{(1)}$

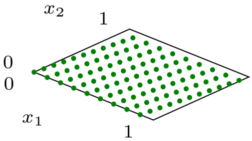


detected frequencies $I^{(2)}$

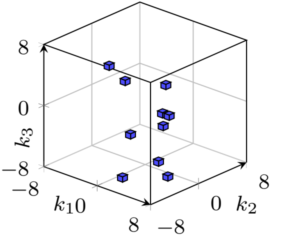


frequency candidates $I^{(1)} \times I^{(2)}$

reconstructing $\longrightarrow$ rank-1 lattice



sampling nodes



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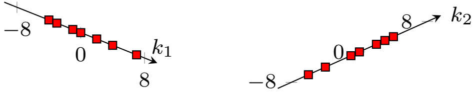
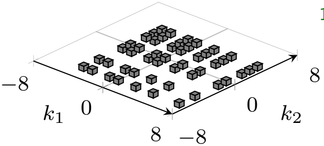


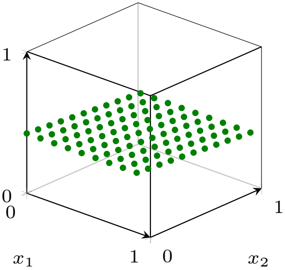
detected frequencies $I^{(1)}$

detected frequencies $I^{(2)}$

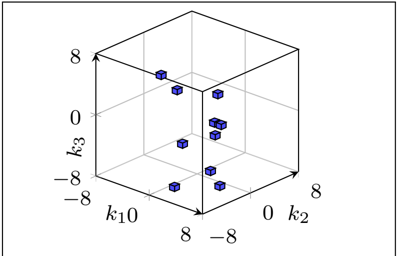


frequency candidates $I^{(1)} \times I^{(2)}$

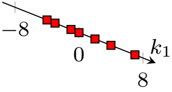
1-dim. FFT



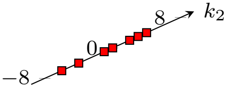
sampling nodes



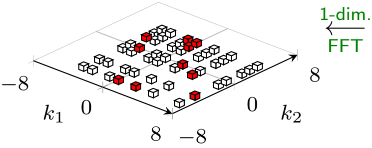
$I \subset \Gamma = \hat{G}_8^3$



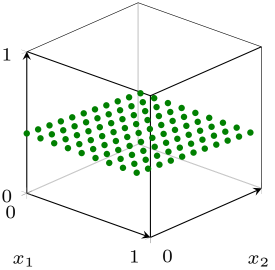
detected frequencies
$I^{(1)}$



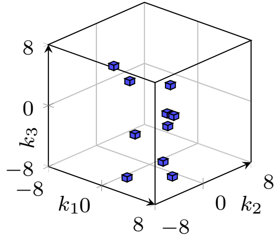
detected frequencies
$I^{(2)}$



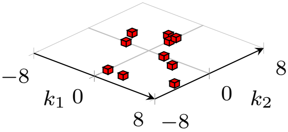
detected frequencies $I^{(1,2)}$



sampling nodes



$I \subset \Gamma = \hat{G}_8^3$

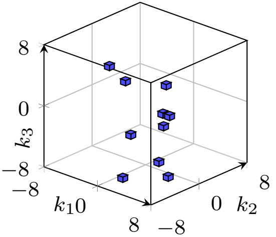


detected frequencies $I^{(1,2)}$

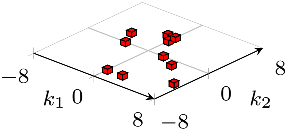
frequency candidates

sampling nodes

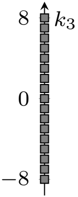
Method



$I \subset \Gamma = \hat{G}_8^3$



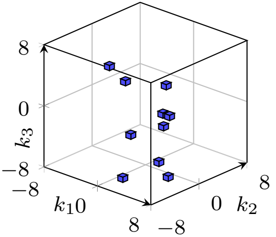
detected frequencies $I^{(1,2)}$



frequency candidates

sampling nodes

High-dimensional dimension-incremental sparse FFT [Potts, V. '15] [V. '17]
Method



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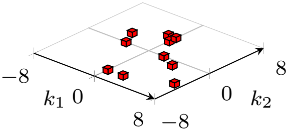
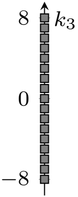
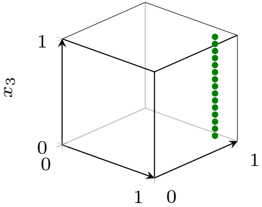


detected frequencies $I^{(1,2)}$

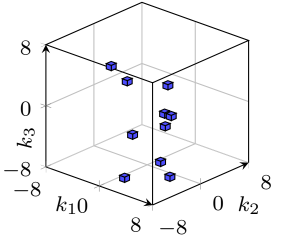


frequency candidates

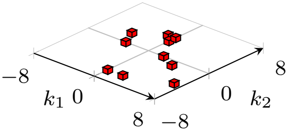
construct $\longrightarrow$ sampling set



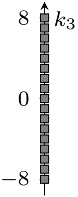
sampling nodes



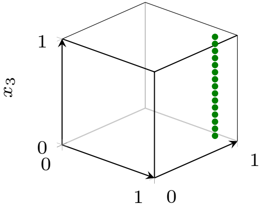
$I \subset \Gamma = \hat{G}_8^3$



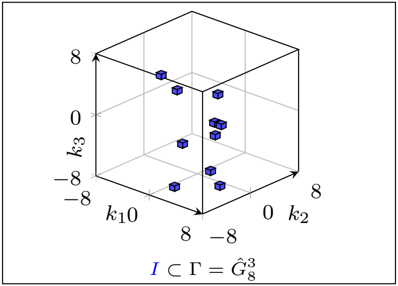
detected frequencies $I^{(1,2)}$

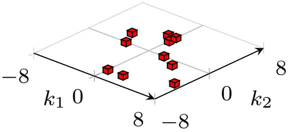


frequency candidates

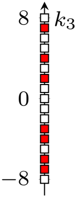


sampling nodes



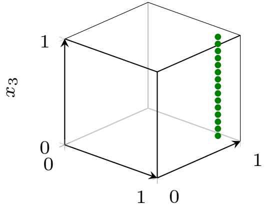


detected frequencies $I^{(1,2)}$

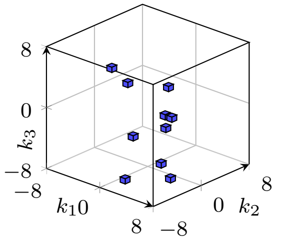


detected frequencies $I^{(3)}$

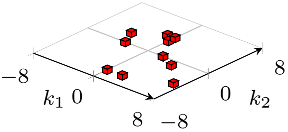
1-dim. ← FFT



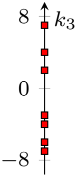
sampling nodes



$I \subset \Gamma = \hat{G}_8^3$



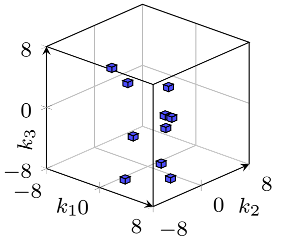
detected frequencies $I^{(1,2)}$



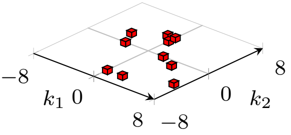
$I^{(3)}$

frequency candidates $I^{(1,2)} \times I^{(3)}$

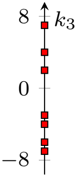
sampling nodes



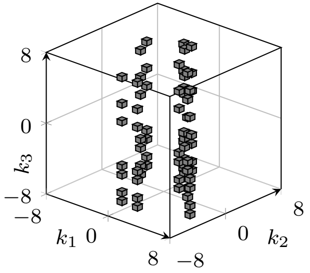
$I \subset \Gamma = \hat{G}_8^3$



detected frequencies $I^{(1,2)}$

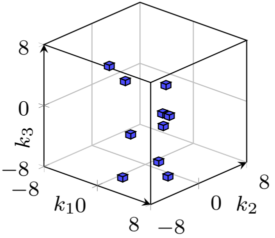


$I^{(3)}$

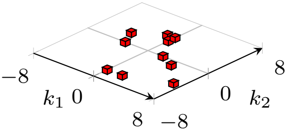


frequency candidates $I^{(1,2)} \times I^{(3)}$

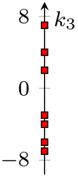
sampling nodes



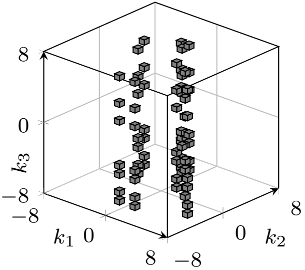
$I \subset \Gamma = \hat{G}_8^3$



detected frequencies $I^{(1,2)}$

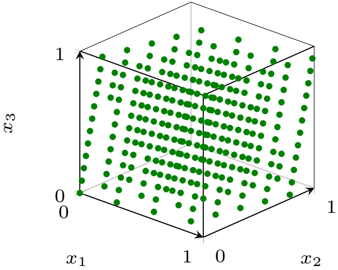


$I^{(3)}$

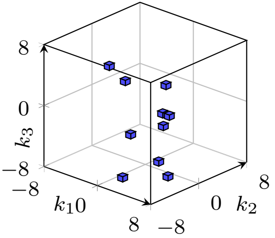


frequency candidates $I^{(1,2)} \times I^{(3)}$

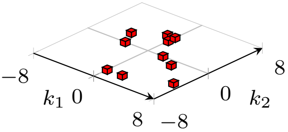
reconstructing
$\longrightarrow$
rank-1 lattice



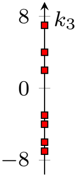
sampling nodes



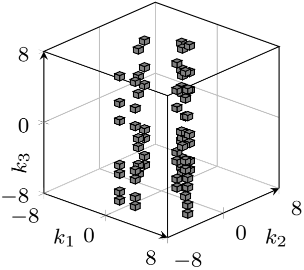
$I \subset \Gamma = \hat{G}_8^3$



detected frequencies $I^{(1,2)}$

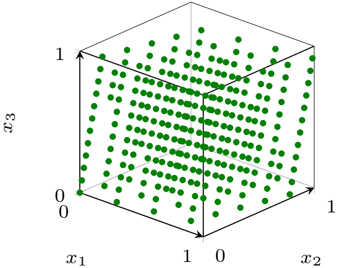


$I^{(3)}$

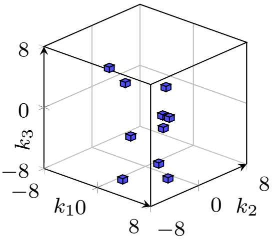


frequencies candidates $I^{(1,2)} \times I^{(3)}$

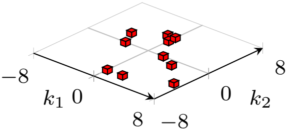
1-dim. ⟵ FFT



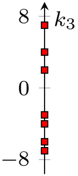
sampling nodes



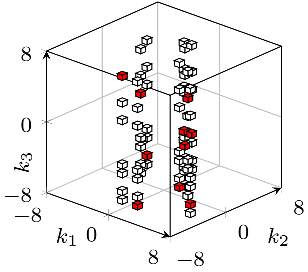
$I \subset \Gamma = \hat{G}_8^3$



detected frequencies $I^{(1,2)}$

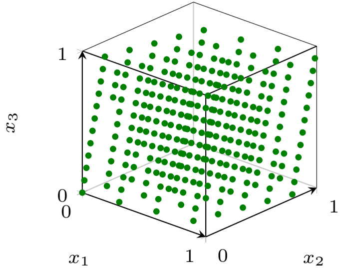


$I^{(3)}$

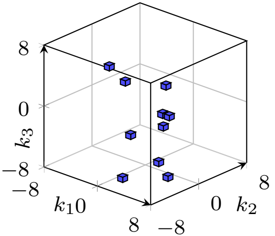


detected frequencies $I^{(1,2,3)} = I$

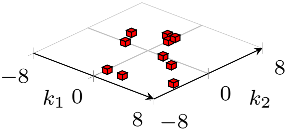
1-dim. ← FFT



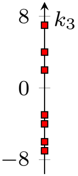
sampling nodes



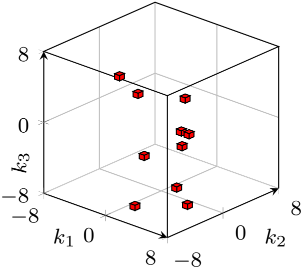
$I \subset \Gamma = \hat{G}_8^3$



detected frequencies $I^{(1,2)}$



$I^{(3)}$



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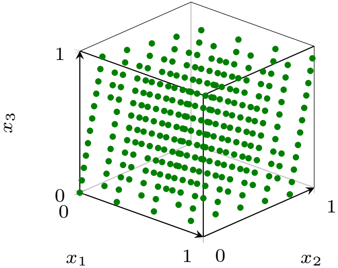


sampling nodes

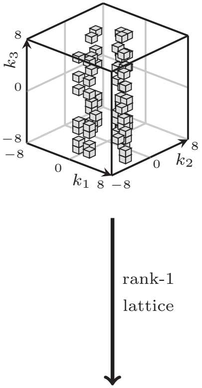
complexity:

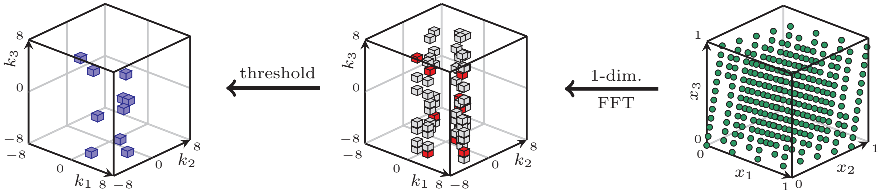
- sparsity $s = |I|$, search domain $\Gamma = \hat{G}_N^d := \{-N, \ldots, N\}^d \supset I$, number of detection iterations $r \in \mathbb{N}$
- samples: $\mathcal{O}(r^2 s^2 N)$
- arithmetic operations: $\mathcal{O}(d\, r^3 s^3 + d\, r^2 s^2 N \log(rsN))$, $\sqrt{N} \lesssim s \lesssim N^d$
- if $(\mathrm{Re}(\hat{p}_{\boldsymbol{k}})$ identical sign) AND $(\mathrm{Im}(\hat{p}_{\boldsymbol{k}})$ identical sign) then deterministic version with $r = 1$ detection iteration

- dimension-incremental method determines sampling set such that all Fourier coefficients $\hat{p}_{\boldsymbol{k}}$ with frequencies $\boldsymbol{k}$ from candidate list can be determined exactly
- other approaches were tested:
  e.g. random sub-sampling + ℓ_1 minimization
  or Prony's method

! problems for noisy / non-sparse case

$\Rightarrow$ new approach: use multiple reconstructing rank-1 lattices





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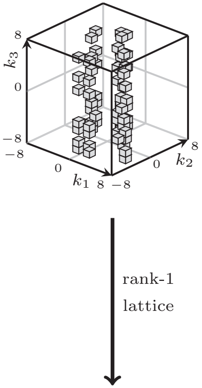

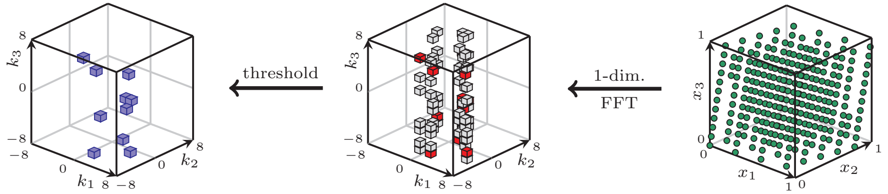

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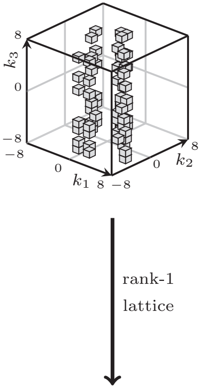
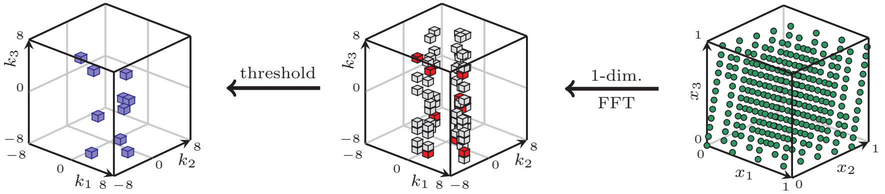
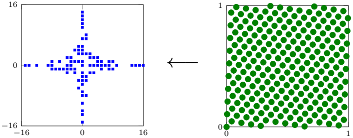




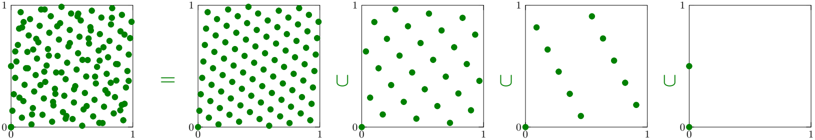
Multiple reconstructing rank-1 lattices [Kämmerer '16] [Kämmerer '17]

- reconstructing $\mathrm{R1L}(\boldsymbol{z}, M, I)$ has size M with $|I| \leq M \leq |I|^2$
  - number of samples: $\mathcal{O}(|I|^2)$
  - construction complexity: $\mathcal{O}(d\,|I|^3)$



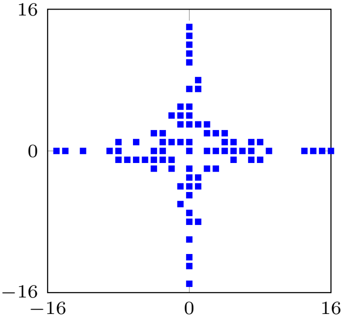
$\Rightarrow$ use more than one rank-1 lattice [Kämmerer '16] [Kämmerer '17]

- perform greedy search for sequence of rank-1 lattices which reconstruct as many as possible frequencies from I



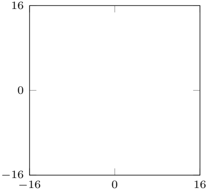
$\Rightarrow$ number of samples: $\mathcal{O}\left(|I| \log^2 |I|\right)$ (w.h.p.), construction complexity: $\mathcal{O}\left(d\,|I| \log^4 |I|\right)$ (w.h.p.)

remaining frequencies to reconstruct:



rank-1 lattice:

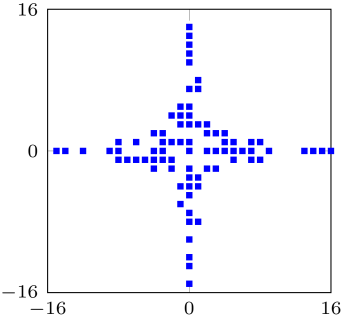
reconstructable freq.:



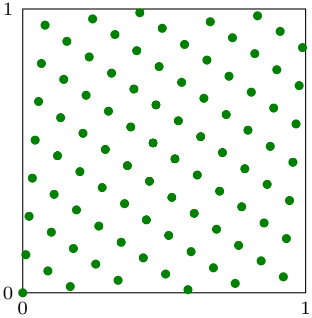
used rank-1 lattices:

Multiple reconstructing rank-1 lattices [Kämmerer '16] [Kämmerer '17]

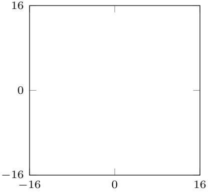
remaining frequencies to reconstruct:



rank-1 lattice:



reconstructable freq.:



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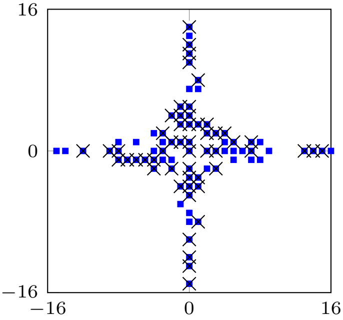
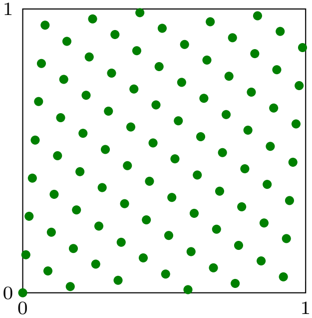
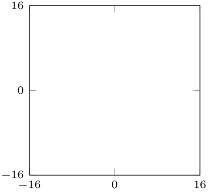


rank-1 lattice:



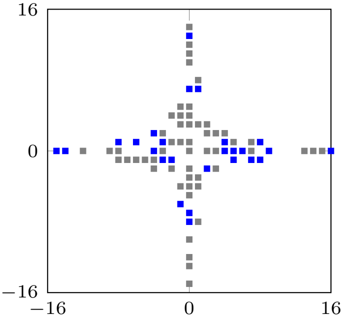
reconstructable freq.:



used rank-1 lattices:

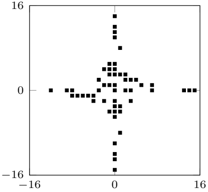
Multiple reconstructing rank-1 lattices [Kämmerer '16] [Kämmerer '17]

remaining frequencies to reconstruct:

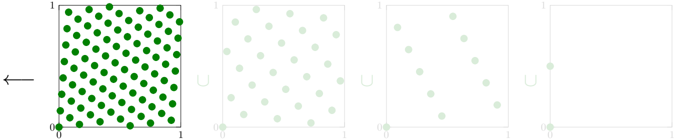


rank-1 lattice:

reconstructable freq.:



used rank-1 lattices:



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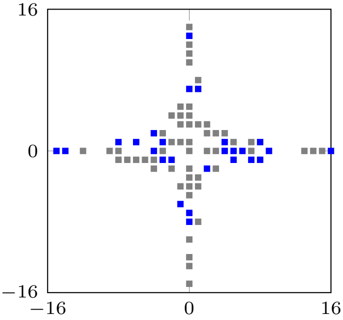
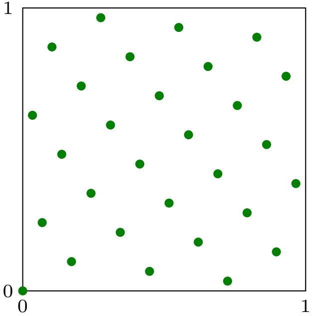
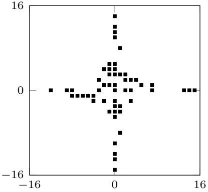


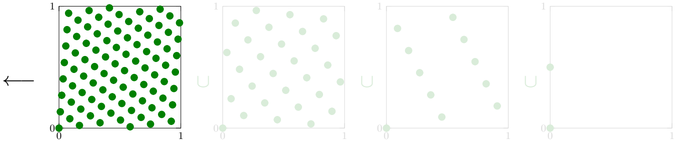
rank-1 lattice:



reconstructable freq.:



used rank-1 lattices:



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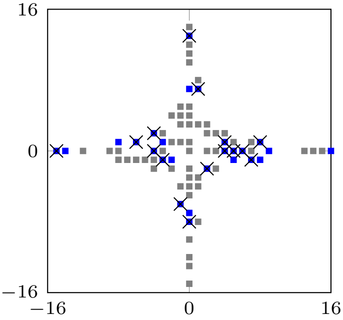

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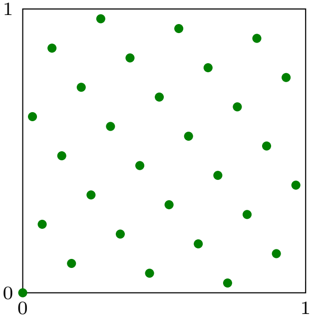

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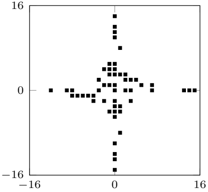
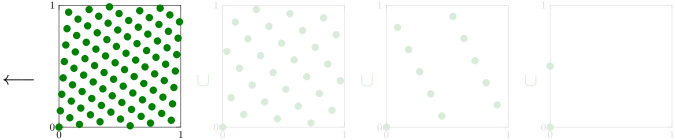


used rank-1 lattices:



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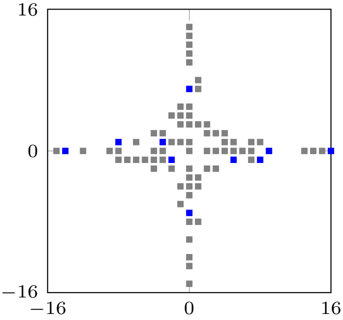

rank-1 lattice:

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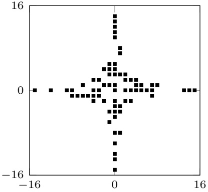
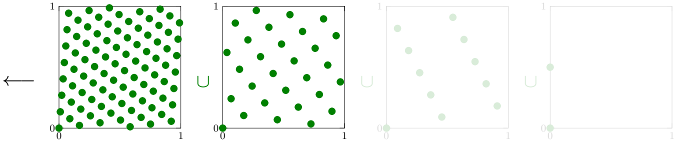


used rank-1 lattices:



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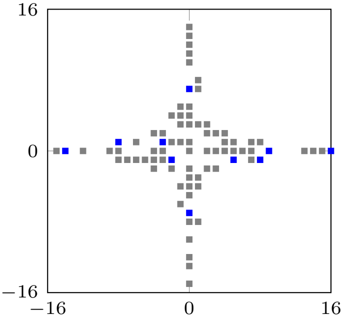

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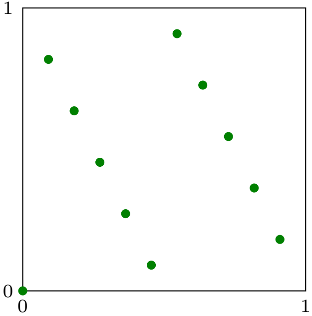
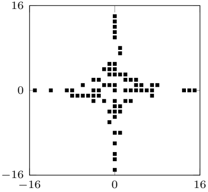
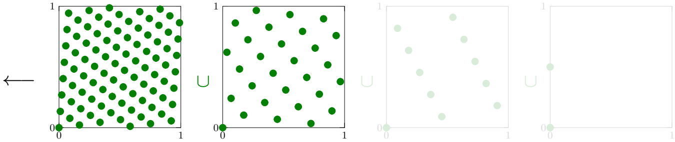


reconstructable freq.:



used rank-1 lattices:



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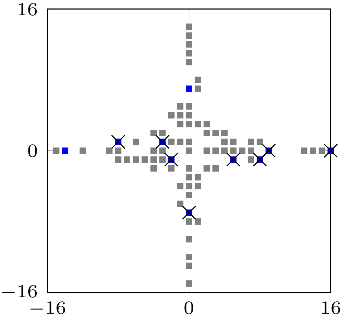

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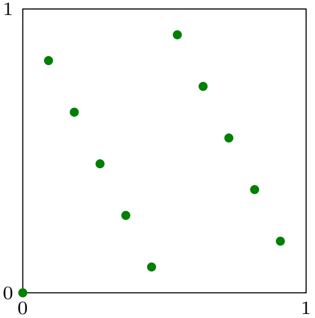

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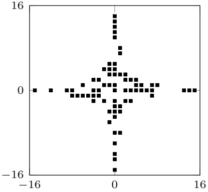
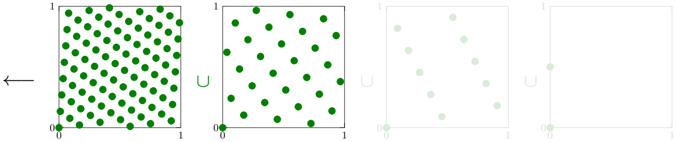


used rank-1 lattices:



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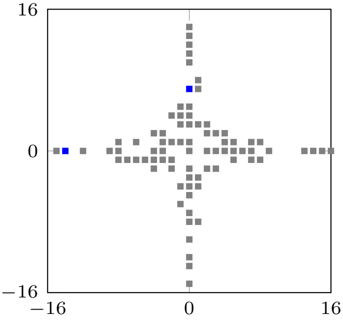
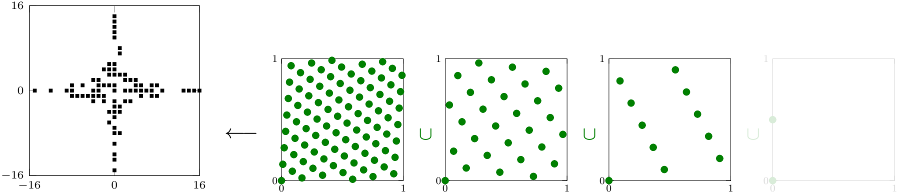


rank-1 lattice:

reconstructable freq.:

used rank-1 lattices:



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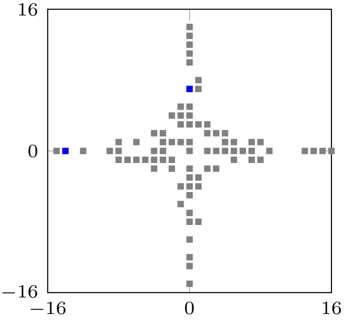

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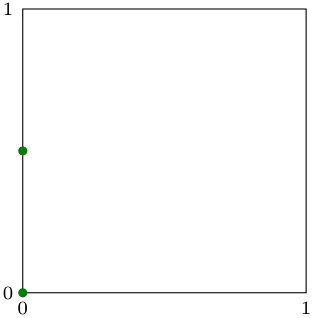
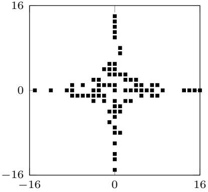
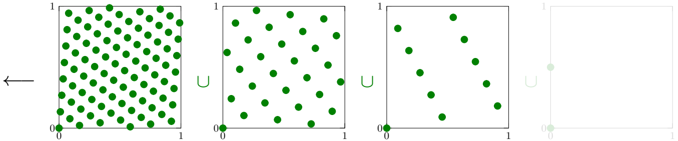


reconstructable freq.:



used rank-1 lattices:



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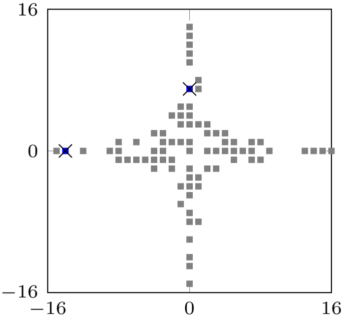

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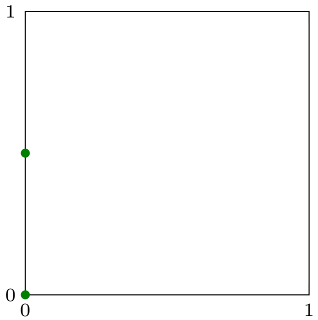

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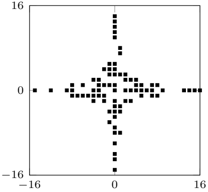

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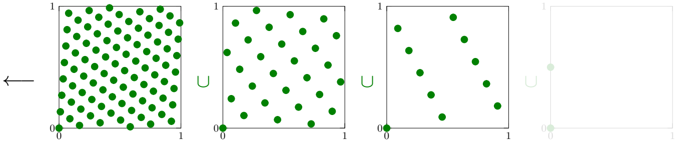

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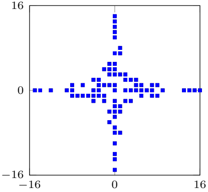

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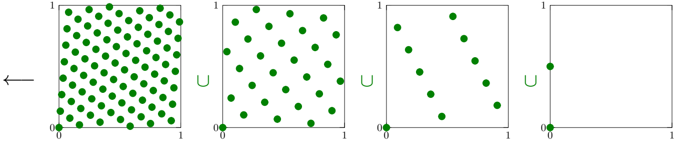

complexity of dimension-incremental sparse FFT using multiple rank-1 lattices:

- sparsity $s = |I|$, search domain $\Gamma = \hat{G}_N^d := \{-N, \ldots, N\}^d \supset I$, number of detection iterations r
- samples: $\mathcal{O}(d\, r s N \log^2(rsN))$ (w.h.p.)
  instead of $\mathcal{O}(d\, r^2 s^2 N)$
- arithmetic operations: $\mathcal{O}\big(d^2 r s N \log^4(rsN)\big)$ (w.h.p.)
  instead of $\mathcal{O}(d\, r^3 s^3 + d\, r^2 s^2 N \log(rsN))$

example: $p_I(\boldsymbol{x}) = \sum_{\boldsymbol{k}\in I} \hat{p}_{\boldsymbol{k}}\, \mathrm{e}^{2\pi\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}}$, $I \subset \Gamma = \hat{G}_{32}^5 := \{-32, \ldots, 32\}^5$, $|\Gamma| \approx 1.16 \cdot 10^9$

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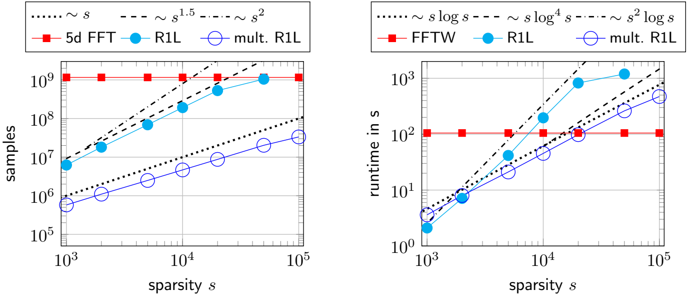

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example:

- B-spline $N_m(x) := \sum_{k\in\mathbb{Z}} C_m \,\mathrm{sinc}\left(\frac{\pi}{m}k\right)^m (-1)^k \,\mathrm{e}^{2\pi\mathrm{i}kx}$
- $f(\boldsymbol{x}) := \prod_{t\in\{1,3,8\}} N_2(x_t) + \prod_{t\in\{2,5,6,10\}} N_4(x_t) + \prod_{t\in\{4,7,9\}} N_6(x_t)$
- dimension-incremental method for $\Gamma = \hat{G}_{64}^{10}$: ($|\hat{G}_{64}^{10}| \approx 1.28 \cdot 10^{21}$)

threshold	single rank-1 lattices #samples	$\lvert I\rvert$	rel. L_2 error	multiple rank-1 lattices #samples	$\lvert I\rvert$	rel. L_2 error
1.0e-02	327 689	493	1.3e-01	246 681	501	5.5e-01
1.0e-03	2 551 143	1 109	1.1e-02	1 441 455	1 205	1.1e-02
1.0e-04	17 198 228	3 009	2.0e-03	7 473 447	3 463	2.1e-03
1.0e-05	132 285 922	7 435	4.8e-04	37 056 491	11 053	4.9e-04

- multivariate periodic functions and rank-1 lattices
  - fast reconstruction of multivariate trigonometric polynomials p_I for arbitrary frequency index sets I [Kämmerer '14]
  - fast approximation [Kämmerer '14], error estimates in [Kämmerer '14] [Kämmerer, Potts, V. '15] [Byrenheid, Kämmerer, Ullrich, V. '16] [V. '17]
- similar results for multivariate non-periodic functions and rank-1 Chebyshev lattices (not in this talk) [Potts, V. '15] [V. '17]
- high-dimensional dimension-incremental sparse FFT and rank-1 lattices [Potts, V. '16] [V. '17]
  - determination of unknown frequency index set I
  - very good numerical results for high-dimensional sparse trigonometric polynomials and for high-dimensional functions (non-sparse in frequency domain)
- high-dimensional dim.-incremental sparse FFT and multiple rank-1 lattices
  - based on multiple reconstructing rank-1 lattices [Kämmerer '16] [Kämmerer '17]
  - distinct reduction of number of samples and arithmetic operations

L. Kämmerer. **High Dimensional Fast Fourier Transform Based on Rank-1 Lattice Sampling**. *Dissertation (PhD thesis), Faculty of Mathematics, Chemnitz University of Technology*, 2014.

L. Kämmerer, D. Potts and T. V. **Approximation of multivariate periodic functions by trigonometric polynomials based on rank-1 lattice sampling.** *J. Complexity*, 31:543–576, 2015.

L. Kämmerer, D. Potts and T. V. **Approximation of multivariate periodic functions by trigonometric polynomials based on sampling along rank-1 lattice with generating vector of Korobov form**. *J. Complexity*, 31:424–456, 2015.

D. Potts and T. V. **Sparse high-dimensional FFT based on rank-1 lattice sampling.** *Appl. Comput. Harmon. Anal.*, 41:713–748, 2016.

G. Byrenheid, L. Kämmerer, T. Ullrich and T. V. **Tight error bounds for rank-1 lattice sampling in spaces of hybrid mixed smoothness.** *Numer. Math.*, 2016, accepted.

L. Kämmerer. **Multiple Rank-1 Lattices as Sampling Schemes for Multivariate Trigonometric Polynomials**. *J. Fourier Anal. Appl.*, 2016.

L. Kämmerer. **Constructing spatial discretizations for sparse multivariate trigonometric polynomials that allow for a fast discrete Fourier transform**. *arXiv:1703.07230*, 2017.

T. V. **Multivariate Approximation and High-Dimensional Sparse FFT Based on Rank-1 Lattice Sampling**. *Dissertation (PhD thesis), Faculty of Mathematics, Chemnitz University of Technology*, 2017.

Software: MATLAB toolboxes (for single rank-1 lattices) `http://www.tu-chemnitz.de/~tovo`