3-Coloring the discrete torus

or

Rigidity of zero temperature 3-states anti-ferromagnetic Potts model

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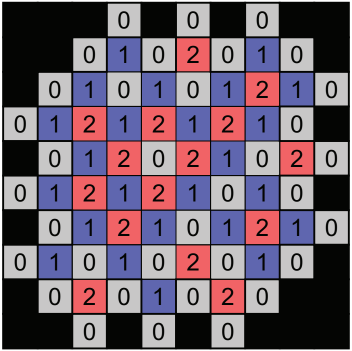
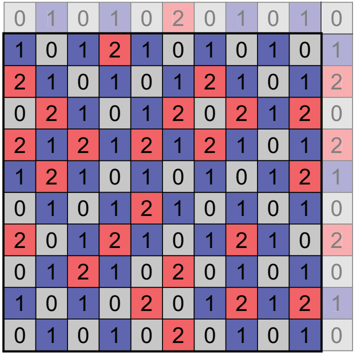
3-Colorings of the Grid/Torus

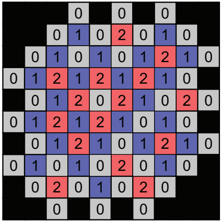


Zero boundary conditions

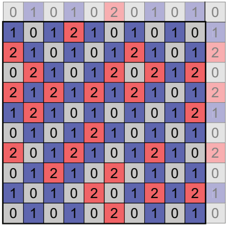


Periodic boundary conditions

Random 3-Colorings



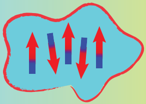
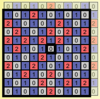
Zero boundary conditions



Periodic boundary conditions

- Uniformly chosen proper 3-coloring (Given boundary conditions)
- High dimension $\mathbb{Z}^d$, and $\mathbb{T}_n^d$.

Additional Motivation

Physics	Mathematical Physics	Combinatorics
		
Antiferromagnetism	*q-states antiferromagnetic Potts model*	`q-colorings of the discrete torus`

- Generalizes the celebrated Ising model.
- Each point takes one of q values.
- Neighbors dislike getting the same color.
- 3-coloring is the “zero temperature” version.

Properties of Interest

In a typical coloring:

- What is the typical relative frequency of the colors? Is it $(1/3, 1/3, 1/3)$?

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- Does it look roughly like this?

1	0	1	0	1	0	2	0	1	0
0	1	0	1	0	1	0	1	0	1
2	0	2	0	1	0	2	0	1	0
0	1	0	2	0	1	0	1	0	1
1	0	2	0	1	0	1	0	1	2
0	1	0	2	0	1	0	2	0	1
2	0	1	0	2	0	1	0	1	0
0	1	0	1	0	2	0	2	0	2
1	0	1	0	2	0	1	0	2	0
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Conjecture:

1	0	1	0	1	0	2	0	1	0
0	1	0	1	0	1	0	1	0	1
2	0	2	0	1	0	2	0	1	0
0	1	0	2	0	1	0	1	0	1
1	0	2	0	1	0	1	0	1	2
0	1	0	2	0	1	0	2	0	1
2	0	1	0	2	0	1	0	1	0
0	1	0	1	0	2	0	2	0	2
1	0	1	0	2	0	1	0	2	0
0	1	0	1	0	2	0	1	0	1

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Conjecture:

$d = 2$ No.

1	0	1	0	1	0	2	0	1	0
0	1	0	1	0	1	0	1	0	1
2	0	2	0	1	0	2	0	1	0
0	1	0	2	0	1	0	1	0	1
1	0	2	0	1	0	1	0	1	2
0	1	0	2	0	1	0	2	0	1
2	0	1	0	2	0	1	0	1	0
0	1	0	1	0	2	0	2	0	2
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1	0	2	0	1	0	1	0	1	2
0	1	0	2	0	1	0	2	0	1
2	0	1	0	2	0	1	0	1	0
0	1	0	1	0	2	0	2	0	2
1	0	1	0	2	0	1	0	2	0
0	1	0	1	0	2	0	1	0	1

Conjecture:

$d = 2$ No.

$d > 2$ Yes.

Past Results - Slow Mixing Time

Indication and application of rigidity

- Glauber dynamics - dynamics on 3-coloring changing one vertex at a time.

1	0	1	0	1	0	2	0	1	0
0	1	0	1	0	1	0	1	0	1
2	0	2	0	1	0	2	0	1	0
0	1	0	2	0	1	0	1	0	1
1	0	2	0	1	0	1	0	1	2
0	1	0	2	0	1	0	2	0	1
2	0	1	0	2	0	1	0	1	0
0	1	0	1	0	2	0	2	0	2
1	0	1	0	2	0	1	0	2	0
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1	0	2	0	1	0	1	0	1	2
0	1	0	2	0	1	0	2	0	1
2	0	1	0	2	0	1	0	1	0
0	1	0	1	0	2	0	2	0	2
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1	0	2	0	1	0	1	0	1	2
0	1	0	2	0	1	0	2	0	1
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- Glauber dynamics - dynamics on 3-coloring changing one vertex at a time.
- Galvin & Randall (2007):
  Torpid mixing for local Markov chains
  (e.g. Glauber dynamics)
- Supports the conjecture that different "phases" exist.

1	0	1	0	1	0	2	0	1	0
0	1	0	1	0	1	0	1	0	1
2	0	2	0	1	0	2	0	1	0
0	1	0	2	0	1	0	1	0	1
1	0	2	0	1	0	1	0	1	2
0	1	0	2	0	1	0	2	0	1
2	0	1	0	2	0	1	0	1	0
0	1	0	1	0	2	0	2	0	2
1	0	1	0	2	0	1	0	2	0
0	1	0	1	0	2	0	1	0	1

1	2	1	2	1	2	0	2	1	2
2	1	2	1	2	1	2	1	2	1
0	2	0	2	1	2	0	2	1	2
2	1	2	0	2	1	2	1	2	1
1	2	0	2	1	2	1	2	1	0
2	1	2	0	2	1	2	0	2	1
0	2	1	2	0	2	1	2	1	2
2	1	2	1	2	0	2	0	2	0
1	2	1	2	0	2	1	2	0	2
2	1	2	1	2	0	2	1	2	1

Past Results - Rigidity for 0-boundary

The conjecture has been established for 0-boundary conditions in high dimension.

0-boundary rigidity (Peled 2010)

In a typical 3-coloring with 0-boundary conditions nearly all the even vertices take the color 0.

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Formally: Let d be large enough, a uniformly chosen 3-coloring with **0-BC**, has:

$$\frac{\mathbb{E}\left|\{v \in V^{even} \;:\; g(v) \neq 0\}\right|}{\left|V^{even}\right|} < \exp\left(-\frac{cd}{\log^2 d}\right).$$

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- Does not work for periodic BC.
- Open in low dimensions.

Past Results - Rigidity for the hypercube

The conjecture has also been supported on bounded tori.

Periodic boundary on the even hypercube (Glavin & Engbers 2011)

For every fixed n, for high enough dimension (depndeing on n), a typical 3-coloring with periodic boundary conditions is nearly constant on either the even or the odd sublattice.

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- Works also for q-colorings (and even more general!)
- Fixed n is less important for physicists.

Our Results - Rigidity on $\mathbb{T}_d^n$

We establish a parallel phenomenon for periodic BC.

Theorem (F., Peled)

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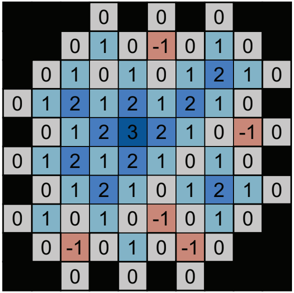
- n must be even.
- Introduces topological techniques to the problem.

Proof Overview

Homomorphism Height Functions

$h : G \to \mathbb{Z}$ satisfying $|h(v) - h(u)| = 1$ if $v \sim u$.



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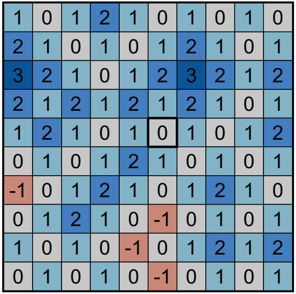

Periodic boundary conditions

- Discretized "topographical map".

Relation to 3-Colorings

On $\mathbb{Z}^d$ there is a a natural bijection.

1	0	1	2	0	1	2	0	1	0
2	1	0	1	2	0	1	2	0	1
1	2	1	0	1	2	0	1	2	0
0	1	0	1	2	1	2	0	1	2
2	0	1	2	1	0	1	2	0	1
0	1	0	1	2	1	2	0	1	2
2	0	1	2	1	2	0	2	0	1
0	1	2	0	2	1	2	0	1	2
1	0	1	2	0	2	0	1	2	0
0	1	0	1	2	0	1	2	0	1

Pointed 3-Colorings

1	0	1	2	3	4	5	6	7	6
2	1	0	1	2	3	4	5	6	7
1	2	1	0	1	2	3	4	5	6
0	1	0	1	2	1	2	3	4	5
-1	0	1	2	1	0	1	2	3	4
0	1	0	1	2	1	2	3	4	5
-1	0	1	2	1	2	3	2	3	4
0	1	2	3	2	1	2	3	4	5
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Pointed HHFs

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0	1	0	1	2	1	2	0	1	2
2	0	1	2	1	0	1	2	0	1
0	1	0	1	2	1	2	0	1	2
2	0	1	2	1	2	0	2	0	1
0	1	2	0	2	1	2	0	1	2
1	0	1	2	0	2	0	1	2	0
0	1	0	1	2	0	1	2	0	1

Pointed 3-Colorings

mod 3

1	0	1	2	3	4	5	6	7	6
2	1	0	1	2	3	4	5	6	7
1	2	1	0	1	2	3	4	5	6
0	1	0	1	2	1	2	3	4	5
-1	0	1	2	1	0	1	2	3	4
0	1	0	1	2	1	2	3	4	5
-1	0	1	2	1	2	3	2	3	4
0	1	2	3	2	1	2	3	4	5
1	0	1	2	3	2	3	4	5	6
0	1	0	1	2	3	4	5	6	7

Pointed HHFs

This bijection does not extend to $\mathbb{T}_n^d$.

Rigidity of HHFs

More is known about HHFs then about 3-colorings:

Rigidity of HHFs on $\mathbb{T}_n^d$ (follows from Peled 2010)

A typical pointed HHF on a high dimensional torus is nearly constant on either the even or the odd sublattice.

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Here Topology enters.

Introducing Quasi-Periodic HHFs

What are 3-colorings on $\mathbb{T}_n^d$ in bijection with?

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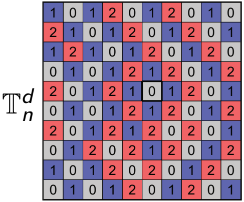
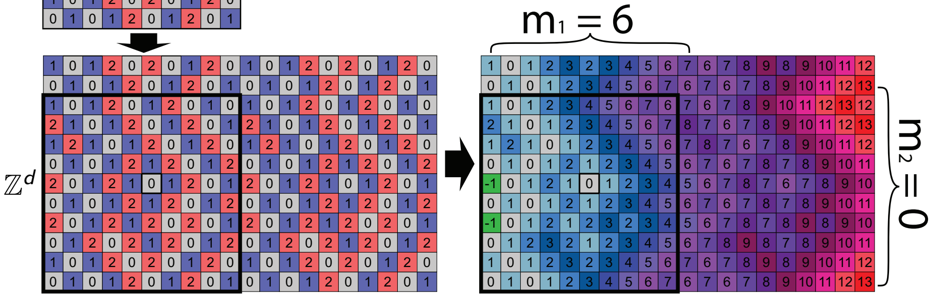


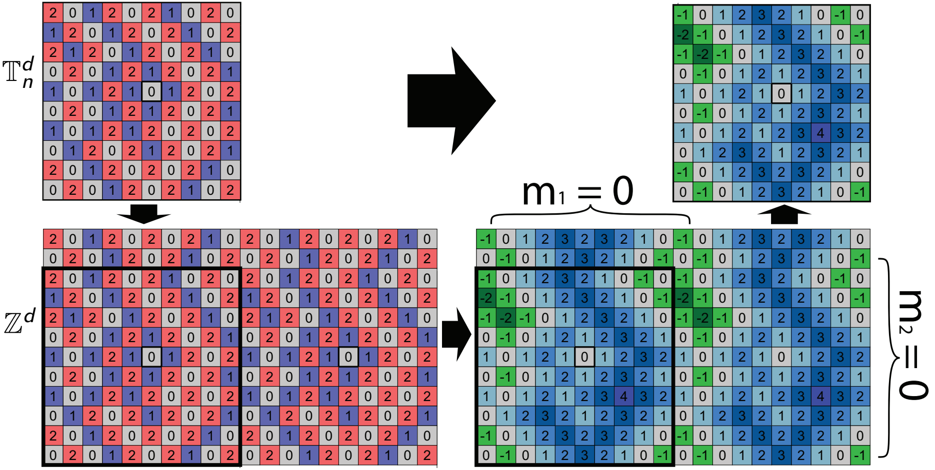
Quasi periodic HHFs of $\mathbb{Z}^d$

whose slopes are 0 mod 6



Flat Slope HHFs $\leftrightarrow$ HHFs on $\mathbb{T}_n^d$

If all slopes are 0 ("flat" coloring) we get an HHF on $\mathbb{T}_n^d$.



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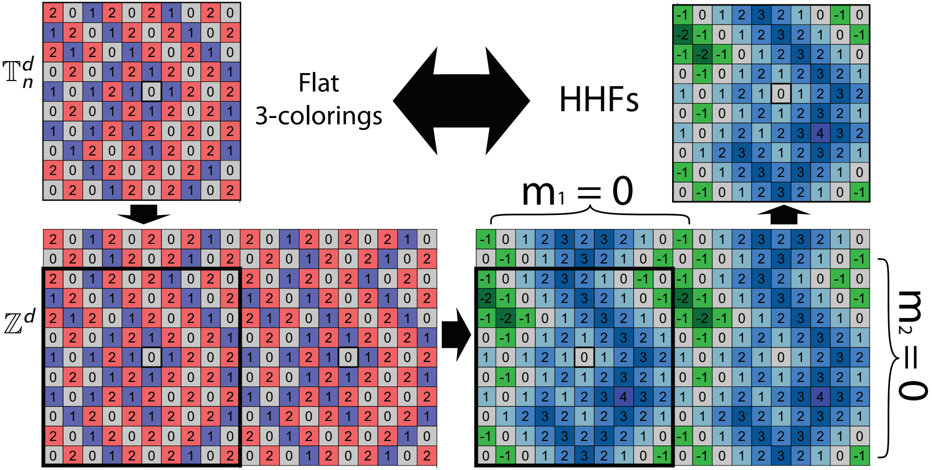


Pulling the HHFs result to 3-colorings

3-colorings of $\mathbb{T}_n^d$

$\updownarrow$

Periodic 3-colorings of $\mathbb{Z}^d$

1	0	1	2	0	2	0	1	2	0	1	0	1	2	0	2	0	1	2	0
0	1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1
1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1	0
2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1	2	0	1
1	2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1	2	0
0	1	0	1	2	1	2	0	1	2	0	1	0	1	2	1	2	0	1	2
2	0	1	2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1
0	1	0	1	2	1	2	0	1	2	0	1	0	1	2	1	2	0	1	2
2	0	1	2	1	2	0	2	0	1	2	0	1	2	1	2	0	2	0	1
0	1	2	0	2	1	2	0	1	2	0	1	2	0	2	1	2	0	1	2
1	0	1	2	0	2	0	1	2	0	1	0	1	2	0	2	0	1	2	0
0	1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1

Pulling the HHFs result to 3-colorings

3-colorings of $\mathbb{T}_n^d$

$\updownarrow$

Periodic 3-colorings of $\mathbb{Z}^d$

$\updownarrow$

Quasi-periodic HHFs on $\mathbb{Z}^d$

1	0	1	2	0	2	0	1	2	0	1	0	1	2	0	2	0	1	2	0
0	1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1
1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1	0
2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1	2	0	1
1	2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1	2	0
0	1	0	1	2	1	2	0	1	2	0	1	0	1	2	1	2	0	1	2
2	0	1	2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1
0	1	0	1	2	1	2	0	1	2	0	1	0	1	2	1	2	0	1	2
2	0	1	2	1	2	0	2	0	1	2	0	1	2	1	2	0	2	0	1
0	1	2	0	2	1	2	0	1	2	0	1	2	0	2	1	2	0	1	2
1	0	1	2	0	2	0	1	2	0	1	0	1	2	0	2	0	1	2	0
0	1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1

1	0	1	2	3	2	3	4	5	6	7	6	7	8	9	8	9	10	11	12
0	1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13
1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13	12
2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10	11	12	13
1	2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10	11	12
0	1	0	1	2	1	2	3	4	5	6	7	6	7	8	7	8	9	10	11
-1	0	1	2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10
0	1	0	1	2	1	2	3	4	5	6	7	6	7	8	7	8	9	10	11
-1	0	1	2	1	2	3	2	3	4	5	6	7	8	7	8	9	8	9	10
0	1	2	3	2	1	2	3	4	5	6	7	8	9	8	7	8	9	10	11
1	0	1	2	3	2	3	4	5	6	7	6	7	8	9	8	9	10	11	12
0	1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13

Pulling the HHFs result to 3-colorings

3-colorings of $\mathbb{T}_n^d$

$\updownarrow$

Periodic 3-colorings of $\mathbb{Z}^d$

$\updownarrow$

Quasi-periodic HHFs on $\mathbb{Z}^d$

Periodic HHFs on $\mathbb{Z}^d$

1	0	1	2	0	2	0	1	2	0	1	0	1	2	0	2	0	1	2	0
0	1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1
1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1	0
2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1	2	0	1
1	2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1	2	0
0	1	0	1	2	1	2	0	1	2	0	1	0	1	2	1	2	0	1	2
2	0	1	2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1
0	1	0	1	2	1	2	0	1	2	0	1	0	1	2	1	2	0	1	2
2	0	1	2	1	2	0	2	0	1	2	0	1	2	1	2	0	2	0	1
0	1	2	0	2	1	2	0	1	2	0	1	2	0	2	1	2	0	1	2
1	0	1	2	0	2	0	1	2	0	1	0	1	2	0	2	0	1	2	0
0	1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1

1	0	1	2	3	2	3	4	5	6	7	6	7	8	9	8	9	10	11	12
0	1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13
1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13	12
2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10	11	12	13
1	2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10	11	12
0	1	0	1	2	1	2	3	4	5	6	7	6	7	8	7	8	9	10	11
-1	0	1	2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10
0	1	0	1	2	1	2	3	4	5	6	7	6	7	8	7	8	9	10	11
-1	0	1	2	1	2	3	2	3	4	5	6	7	8	7	8	9	8	9	10
0	1	2	3	2	1	2	3	4	5	6	7	8	9	8	7	8	9	10	11
1	0	1	2	3	2	3	4	5	6	7	6	7	8	9	8	9	10	11	12
0	1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13

Pulling the HHFs result to 3-colorings

3-colorings of $\mathbb{T}_n^d$

$\updownarrow$

Periodic 3-colorings of $\mathbb{Z}^d$

$\updownarrow$

Quasi-periodic HHFs on $\mathbb{Z}^d$

Periodic HHFs on $\mathbb{Z}^d$

$\updownarrow$

HHFs on $\mathbb{T}_n^d$

1	0	1	2	0	2	0	1	2	0	1	0	1	2	0	2	0	1	2	0
0	1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1
1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1	0
2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1	2	0	1
1	2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1	2	0
0	1	0	1	2	1	2	0	1	2	0	1	0	1	2	1	2	0	1	2
2	0	1	2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1
0	1	0	1	2	1	2	0	1	2	0	1	0	1	2	1	2	0	1	2
2	0	1	2	1	2	0	2	0	1	2	0	1	2	1	2	0	2	0	1
0	1	2	0	2	1	2	0	1	2	0	1	2	0	2	1	2	0	1	2
1	0	1	2	0	2	0	1	2	0	1	0	1	2	0	2	0	1	2	0
0	1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1

1	0	1	2	3	2	3	4	5	6	7	6	7	8	9	8	9	10	11	12
0	1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13
1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13	12
2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10	11	12	13
1	2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10	11	12
0	1	0	1	2	1	2	3	4	5	6	7	6	7	8	7	8	9	10	11
-1	0	1	2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10
0	1	0	1	2	1	2	3	4	5	6	7	6	7	8	7	8	9	10	11
-1	0	1	2	1	2	3	2	3	4	5	6	7	8	7	8	9	8	9	10
0	1	2	3	2	1	2	3	4	5	6	7	8	9	8	7	8	9	10	11
1	0	1	2	3	2	3	4	5	6	7	6	7	8	9	8	9	10	11	12
0	1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13

Pulling the HHFs result to 3-colorings

3-colorings of $\mathbb{T}_n^d$

$\updownarrow$

Periodic 3-colorings of $\mathbb{Z}^d$

$\updownarrow$

Quasi-periodic HHFs on $\mathbb{Z}^d$

Periodic HHFs on $\mathbb{Z}^d$

$\updownarrow$

HHFs on $\mathbb{T}_n^d$
(which are known to be rigid)

1	0	1	2	0	2	0	1	2	0	1	0	1	2	0	2	0	1	2	0
0	1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1
1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1	0
2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1	2	0	1
1	2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1	2	0
0	1	0	1	2	1	2	0	1	2	0	1	0	1	2	1	2	0	1	2
2	0	1	2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1
0	1	0	1	2	1	2	0	1	2	0	1	0	1	2	1	2	0	1	2
2	0	1	2	1	2	0	2	0	1	2	0	1	2	1	2	0	2	0	1
0	1	2	0	2	1	2	0	1	2	0	1	2	0	2	1	2	0	1	2
1	0	1	2	0	2	0	1	2	0	1	0	1	2	0	2	0	1	2	0
0	1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1

1	0	1	2	3	2	3	4	5	6	7	6	7	8	9	8	9	10	11	12
0	1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13
1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13	12
2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10	11	12	13
1	2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10	11	12
0	1	0	1	2	1	2	3	4	5	6	7	6	7	8	7	8	9	10	11
-1	0	1	2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10
0	1	0	1	2	1	2	3	4	5	6	7	6	7	8	7	8	9	10	11
-1	0	1	2	1	2	3	2	3	4	5	6	7	8	7	8	9	8	9	10
0	1	2	3	2	1	2	3	4	5	6	7	8	9	8	7	8	9	10	11
1	0	1	2	3	2	3	4	5	6	7	6	7	8	9	8	9	10	11	12
0	1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13

Pulling the HHFs result to 3-colorings

3-colorings of $\mathbb{T}_n^d$

$\updownarrow$

Periodic 3-colorings of $\mathbb{Z}^d$

$\updownarrow$

Quasi-periodic HHFs on $\mathbb{Z}^d$

$\wr\wr$

Periodic HHFs on $\mathbb{Z}^d$

$\updownarrow$

HHFs on $\mathbb{T}_n^d$
(which are known to be rigid)

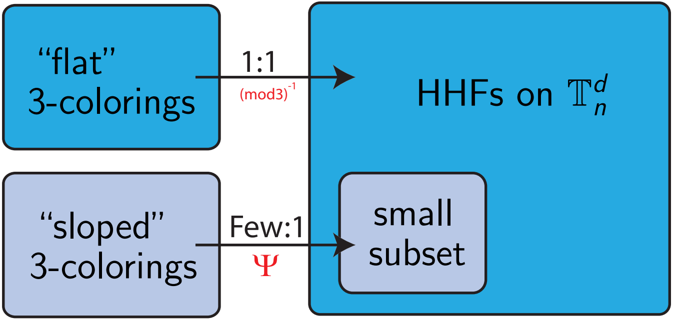
GOAL: Show that most quasi-periodic HHFs are periodic.

1	0	1	2	0	2	0	1	2	0	1	0	1	2	0	2	0	1	2	0
0	1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1
1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1	0
2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1	2	0	1
1	2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1	2	0
0	1	0	1	2	1	2	0	1	2	0	1	0	1	2	1	2	0	1	2
2	0	1	2	1	0	1	2	0	1	2	0	1	2	1	0	1	2	0	1
0	1	0	1	2	1	2	0	1	2	0	1	0	1	2	1	2	0	1	2
2	0	1	2	1	2	0	2	0	1	2	0	1	2	1	2	0	2	0	1
0	1	2	0	2	1	2	0	1	2	0	1	2	0	2	1	2	0	1	2
1	0	1	2	0	2	0	1	2	0	1	0	1	2	0	2	0	1	2	0
0	1	0	1	2	0	1	2	0	1	0	1	0	1	2	0	1	2	0	1

1	0	1	2	3	2	3	4	5	6	7	6	7	8	9	8	9	10	11	12
0	1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13
1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13	12
2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10	11	12	13
1	2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10	11	12
0	1	0	1	2	1	2	3	4	5	6	7	6	7	8	7	8	9	10	11
-1	0	1	2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10
0	1	0	1	2	1	2	3	4	5	6	7	6	7	8	7	8	9	10	11
-1	0	1	2	1	2	3	2	3	4	5	6	7	8	7	8	9	8	9	10
0	1	2	3	2	1	2	3	4	5	6	7	8	9	8	7	8	9	10	11
1	0	1	2	3	2	3	4	5	6	7	6	7	8	9	8	9	10	11	12
0	1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13

Proving Most Quasi-periodic are Periodic

We construct a "flattening" map Ψ from quasi-periodic HHFs into periodic ones.



Flattening the slope

Introducing the reflection Ψ

- Denote $\mathrm{QP}_m := \{h \in \mathrm{QP} : m \text{ is the slope of } h\}$
- We construct $\Psi_m : \mathrm{QP}_m \to \mathrm{QP}_0$, a one-to-one mapping.

1	0	1	2	3	2	3	4	5	6	7	6	7	8	9	8	9	10	11	12
0	1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13
1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13	12
2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10	11	12	13
1	2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10	11	12
0	1	0	1	2	1	2	3	4	5	6	7	6	7	8	7	8	9	10	11
-1	0	1	2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10
0	1	0	1	2	1	2	3	4	5	6	7	6	7	8	7	8	9	10	11
-1	0	1	2	1	2	3	2	3	4	5	6	7	8	7	8	9	8	9	10
0	1	2	3	2	1	2	3	4	5	6	7	8	9	8	7	8	9	10	11
1	0	1	2	3	2	3	4	5	6	7	6	7	8	9	8	9	10	11	12
0	1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13

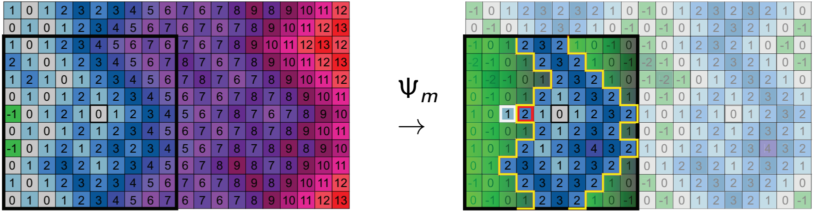
Ψ_m
$\to$

-1	0	1	2	3	2	3	2	1	0	-1	0	1	2	3	2	3	2	1	0
0	-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1
-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1	0
-2	-1	0	1	2	3	2	1	0	-1	-2	-1	0	1	2	3	2	1	0	-1
-1	-2	-1	0	1	2	3	2	1	0	-1	-2	-1	0	1	2	3	2	1	0
0	-1	0	1	2	1	2	3	2	1	0	-1	0	1	2	1	2	3	2	1
1	0	1	2	1	0	1	2	3	2	1	0	1	2	1	0	1	2	3	2
0	-1	0	1	2	1	2	3	2	1	0	-1	0	1	2	1	2	3	2	1
1	0	1	2	1	2	3	4	3	2	1	0	1	2	1	2	3	4	3	2
0	1	2	3	2	1	2	3	2	1	0	1	2	3	2	1	2	3	2	1
-1	0	1	2	3	2	3	2	1	0	-1	0	1	2	3	2	3	2	1	0
0	-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1

Flattening the slope

Introducing the reflection Ψ

- Denote $QP_m := \{h \in QP : m \text{ is the slope of } h\}$
- We construct $\Psi_m : QP_m \to QP_0$, a one-to-one mapping.

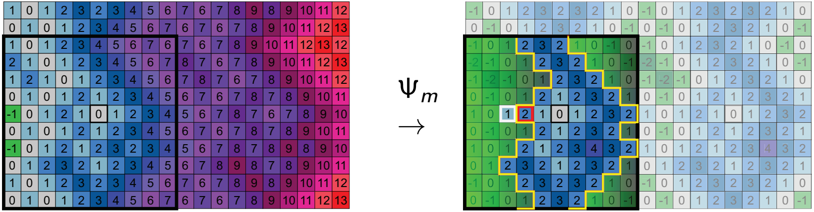


- Observe that the image contains a long level set.

Flattening the slope

Introducing the reflection Ψ

- Denote $\mathrm{QP}_m := \{h \in \mathrm{QP} : m \text{ is the slope of } h\}$
- We construct $\Psi_m : \mathrm{QP}_m \to \mathrm{QP}_0$, a one-to-one mapping.



- Observe that the image contains a long level set.
- Peled 2010: Long level sets are extremely uncommon.

Flattening the slope

Introducing the reflection Ψ

- Denote $QP_m := \{h \in QP : m \text{ is the slope of } h\}$
- We construct $\Psi_m : QP_m \to QP_0$, a one-to-one mapping.

1	0	1	2	3	2	3	4	5	6	7	6	7	8	9	8	9	10	11	12
0	1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13
1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13	12
2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10	11	12	13
1	2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10	11	12
0	1	0	1	2	1	2	3	4	5	6	7	6	7	8	7	8	9	10	11
-1	0	1	2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10
0	1	0	1	2	1	2	3	4	5	6	7	6	7	8	7	8	9	10	11
-1	0	1	2	1	2	3	2	3	4	5	6	7	8	7	8	9	8	9	10
0	1	2	3	2	1	2	3	4	5	6	7	8	9	8	7	8	9	10	11
1	0	1	2	3	2	3	4	5	6	7	6	7	8	9	8	9	10	11	12
0	1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13

Ψ_m
$\to$

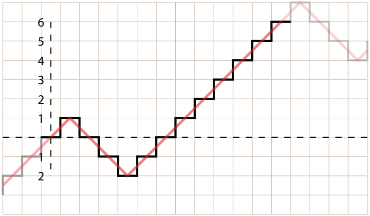
-1	0	1	2	3	2	3	2	1	0	-1	0	1	2	3	2	3	2	1	0
0	-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1
-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1	0
-2	-1	0	1	2	3	2	1	0	-1	-2	-1	0	1	2	3	2	1	0	-1
-1	-2	-1	0	1	2	3	2	1	0	-1	-2	-1	0	1	2	3	2	1	0
0	-1	0	1	2	1	2	3	2	1	0	-1	0	1	2	1	2	3	2	1
1	0	1	2	1	0	1	2	3	2	1	0	1	2	1	0	1	2	3	2
0	-1	0	1	2	1	2	3	2	1	0	-1	0	1	2	1	2	3	2	1
1	0	1	2	1	2	3	4	3	2	1	0	1	2	1	2	3	4	3	2
0	1	2	3	2	1	2	3	2	1	0	1	2	3	2	1	2	3	2	1
-1	0	1	2	3	2	3	2	1	0	-1	0	1	2	3	2	3	2	1	0
0	-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1

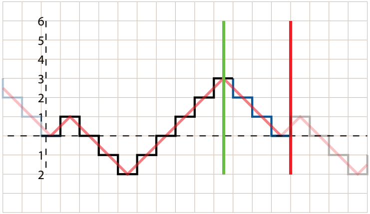
- Observe that the image contains a long level set.
- Peled 2010: Long level sets are extremely uncommon.
- We deduce the image of Ψ_m is small.

Ideas and Method

Flattening Intuition

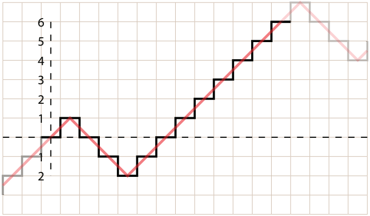
- One-dimensional intuition: reflection.

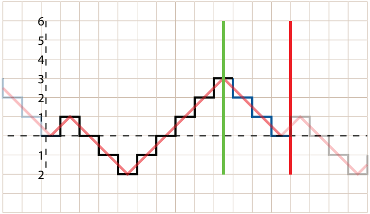




Flattening Intuition

- One-dimensional intuition: reflection.
- Where to reflect?





Flattening Intuition

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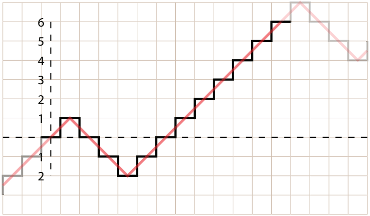

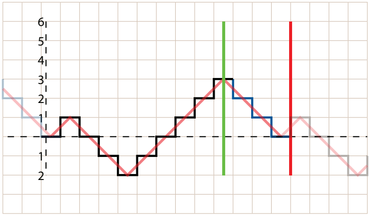

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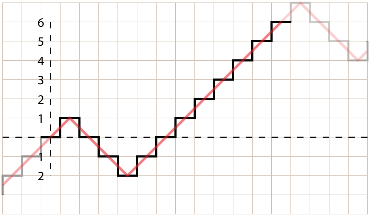
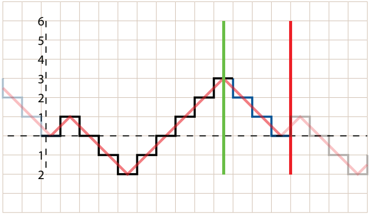
Answer:

Topology says - Yes.

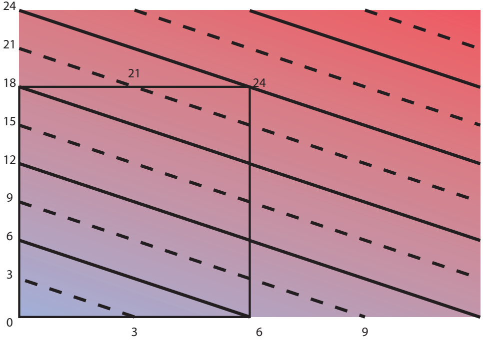




Flattening in Several Dimensions - I

- Linear functions - an instructive example.

Take for example: $f(x, y) = 6x + 18y$.



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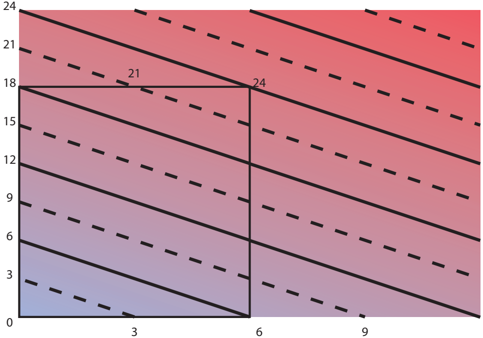

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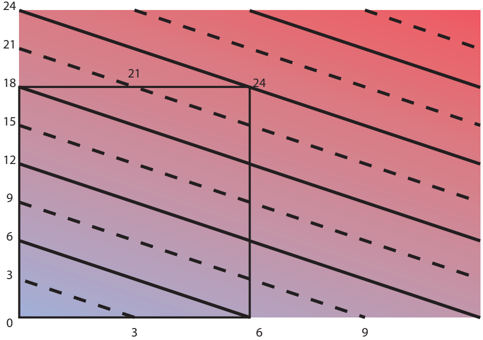

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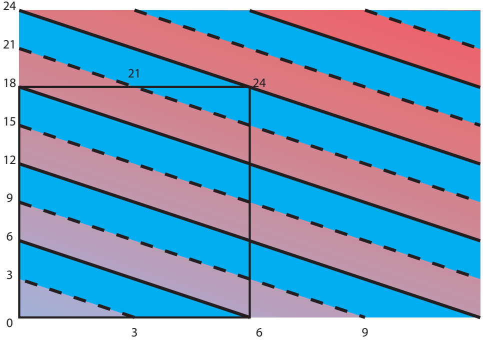

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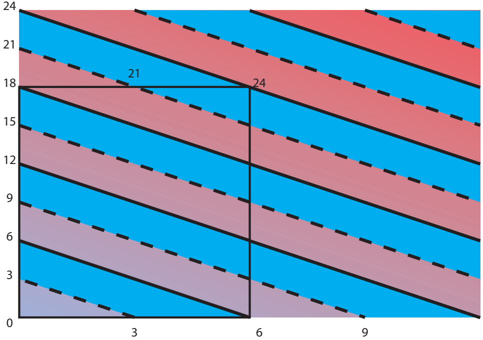

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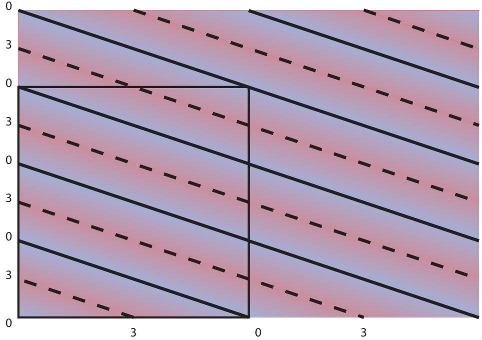

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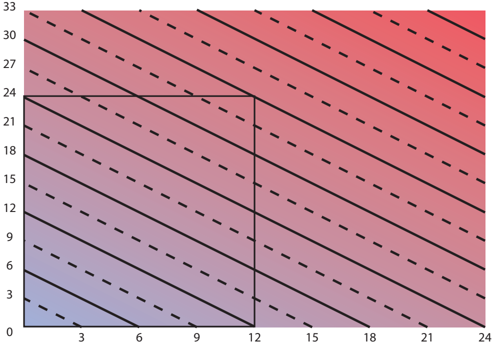
Flattening in Several Dimensions - II

Another linear function: $f(x, y) = 12x + 24y$.



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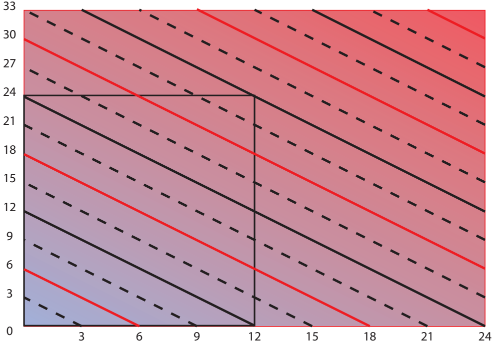

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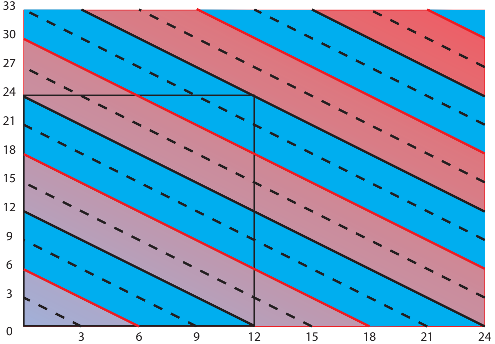

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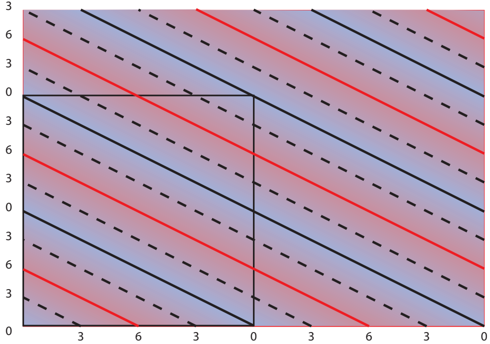
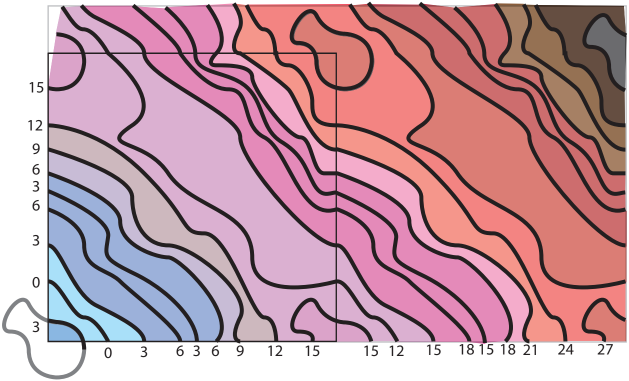


- Two different 0 mod 6 level contours.
- We take mod 12 instead.
- General principle: reflect around $\frac{\gcd(m_1,\ldots,m_n)}{2}$.

Non-linear function

Quasi-periodic functions are homotopy equivalent to linear ones.



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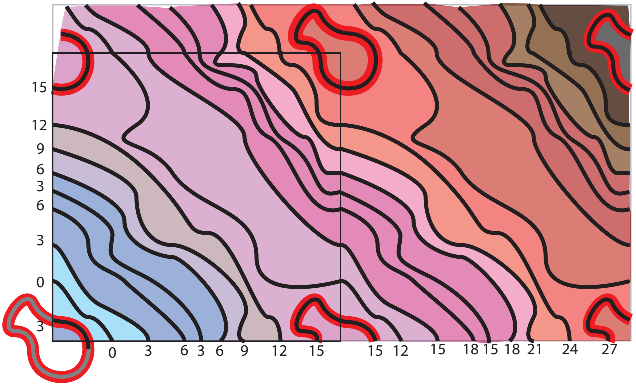

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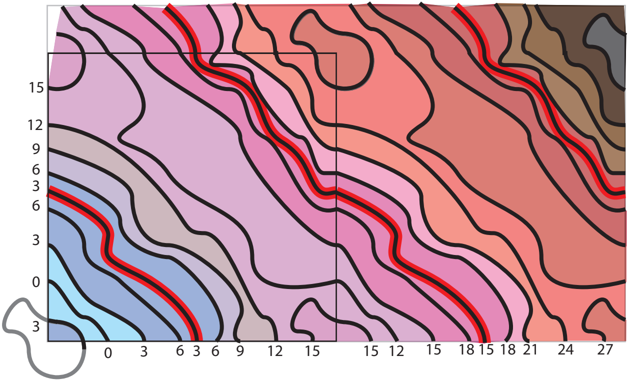

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  Trivial level contours.
  Non-Trivial level contours.

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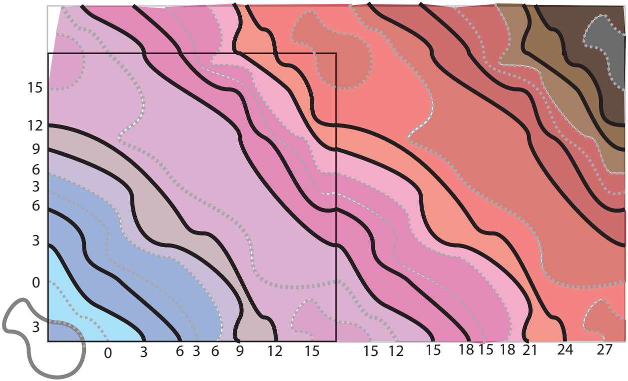

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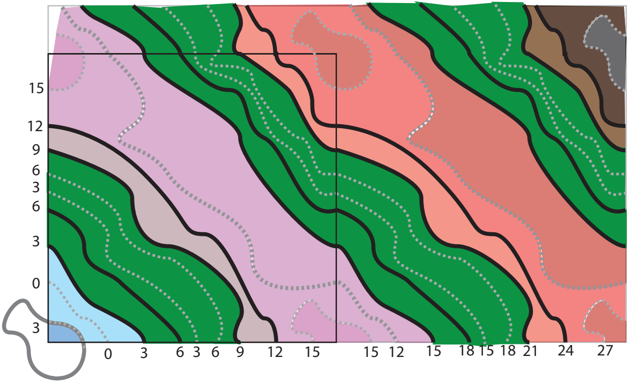

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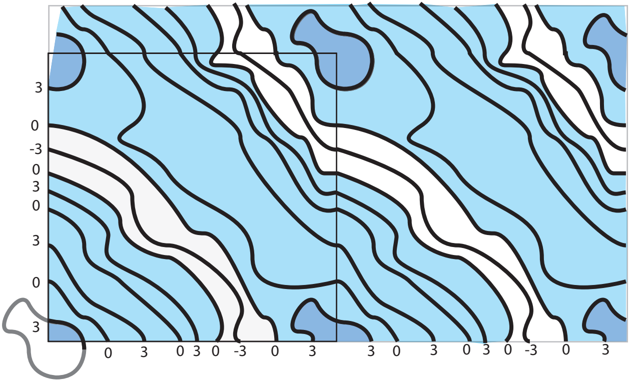

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- We find the proper reflection "modulo".
- We make the reflection.

How to discretize?

Challenges of the discrete setting:

- Define level sets properly.
- Establish their structure.
- Identify trivial level sets.
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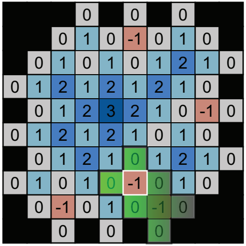
We will focus on these in this presentation.

Level Components

Towards level sets

Level component of v at height k

$LC_h^k(v)$ is the connected component of v in $G \setminus \{u \in G \mid h(u) = k\}$

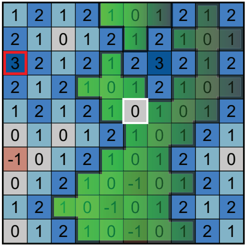


Level Components

The fundament of level sets

Level component from v to u at height k

$\mathrm{LC}_h^k(v,u)$ is the complement of the connected component of u in $G \setminus \mathrm{LC}_h^k(v)$



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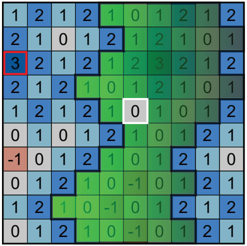

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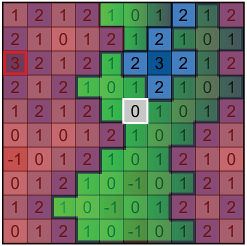

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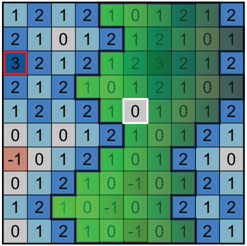

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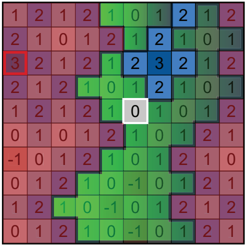

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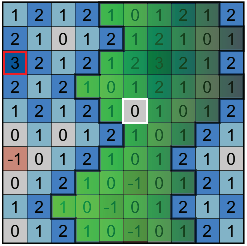

$LC_h^k(v,u)$

The edge boundary of a level component is called a level set.

3 Types of Level Components

A trichotomy

For $t \in n\mathbb{Z}^d$, and a set $U \subset \mathbb{Z}^d$ we call $U + t$ a translate of U.

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3 types of level components

Let $U = \mathrm{LC}_h^k(u, v)$ be a level component with non-empty boundary. One of the following holds:

- (Trivial) All of U's translates are disjoint.
- (Trivial) All of U^c's translates are disjoint.
- (Non-trivial) The translates of U are totally ordered by inclusion.

Trichotomy - example

-1	0	1	2	3	2	3	2	1	0	-1	0	1	2	3	2	3	2	1	0
0	-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1
-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1	0
-2	-1	0	1	2	3	2	1	0	-1	-2	-1	0	1	2	3	2	1	0	-1
-1	-2	-1	0	1	2	3	2	1	0	-1	-2	-1	0	1	2	3	2	1	0
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-1	0	1	2	3	2	3	2	1	0	-1	0	1	2	3	2	3	2	1	0
0	-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1

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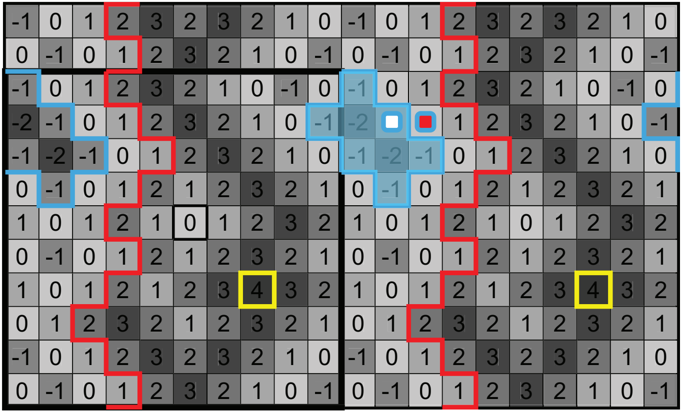

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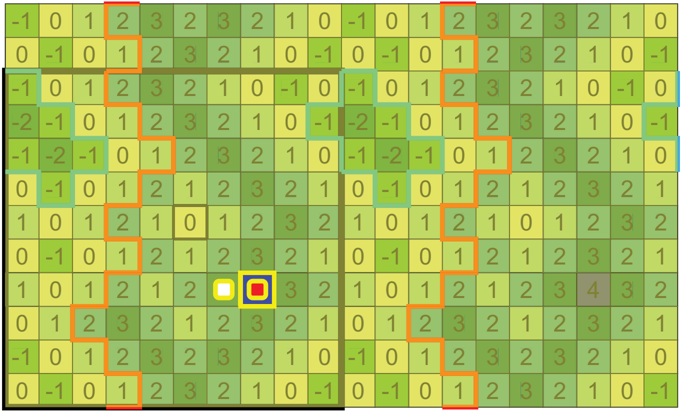
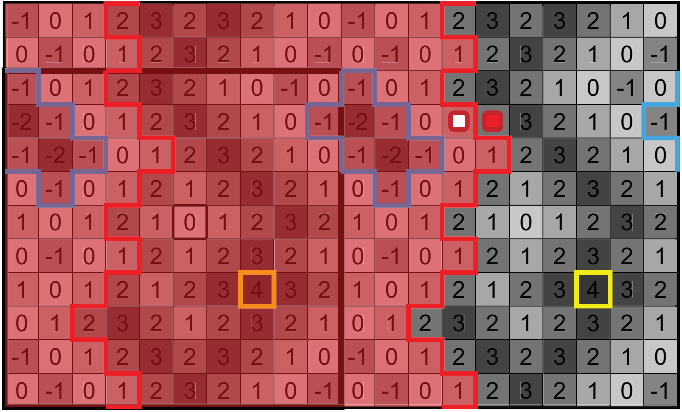


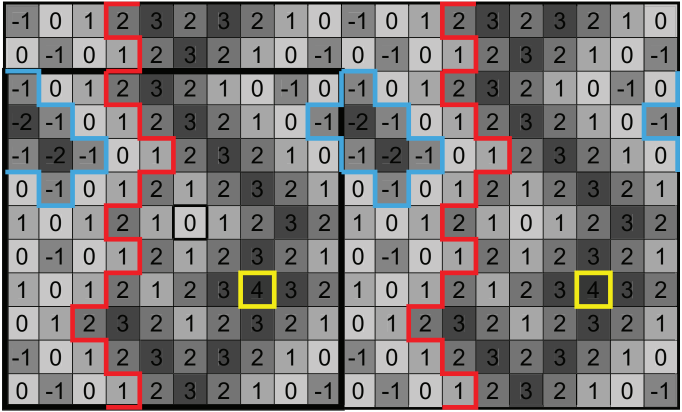
Trivial (Disjoint complement translates)

Trichotomy - example



Non-Trivial (Ordered)

Trichotomy - example



Trivial level components do not create slope.

Formula for heights

Denote $\mathcal{L} = \{A : \exists u_1, u_2 \in \mathbb{Z}^d : A = LC_h^{h(u_2)}(u_1, u_2)\}$

Formula for $h(u) - h(v)$

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-1	0	1	2	3	2	3	2	1	0	-1	0	1	2	3	2	3	2	1	0
0	-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1
-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1	0
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0	-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1

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- Used, for example, to show the existence of non-trivial level components for sloped function.

The Discrete Picture

1	0	1	2	3	2	3	4	5	6	7	6	7	8	9	8	9	10	11	12
0	1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13
1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13	12
2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10	11	12	13
1	2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10	11	12
0	1	0	1	2	1	2	3	4	5	6	7	6	7	8	7	8	9	10	11
-1	0	1	2	1	0	1	2	3	4	5	6	7	8	7	6	7	8	9	10
0	1	0	1	2	1	2	3	4	5	6	7	6	7	8	7	8	9	10	11
-1	0	1	2	1	2	3	2	3	4	5	6	7	8	7	8	9	8	9	10
0	1	2	3	2	1	2	3	4	5	6	7	8	9	8	7	8	9	10	11
1	0	1	2	3	2	3	4	5	6	7	6	7	8	9	8	9	10	11	12
0	1	0	1	2	3	4	5	6	7	6	7	6	7	8	9	10	11	12	13

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-1	0	1	2	3	2	3	2	1	0	-1	0	1	2	3	2	3	2	1	0
0	-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1
-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1	0
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-1	0	1	2	3	2	3	2	1	0	-1	0	1	2	3	2	3	2	1	0
0	-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1

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-1	0	1	2	3	2	3	2	1	0	-1	0	1	2	3	2	3	2	1	0
0	-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1
-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1	0
-2	-1	0	1	2	3	2	1	0	-1	-2	-1	0	1	2	3	2	1	0	-1
-1	-2	-1	0	1	2	3	2	1	0	-1	-2	-1	0	1	2	3	2	1	0
0	-1	0	1	2	1	2	3	2	1	0	-1	0	1	2	1	2	3	2	1
1	0	1	2	1	0	1	2	3	2	1	0	1	2	1	0	1	2	3	2
0	-1	0	1	2	1	2	3	2	1	0	-1	0	1	2	1	2	3	2	1
1	0	1	2	1	2	3	4	3	2	1	0	1	2	1	2	3	4	3	2
0	1	2	3	2	1	2	3	2	1	0	1	2	3	2	1	2	3	2	1
-1	0	1	2	3	2	3	2	1	0	-1	0	1	2	3	2	3	2	1	0
0	-1	0	1	2	3	2	1	0	-1	0	-1	0	1	2	3	2	1	0	-1

Open Problems

Ordered by estimated difficulty

- Odd Tori.

Open Problems
Ordered by estimated difficulty

- Odd Tori.
- 4-colors and more.

Open Problems
Ordered by estimated difficulty

- Odd Tori.
- 4-colors and more.
- Non-zero temperature.

Open Problems

Ordered by estimated difficulty

- Odd Tori.
- 4-colors and more.
- Non-zero temperature.
- Low dimension.

Thank you