Billiards

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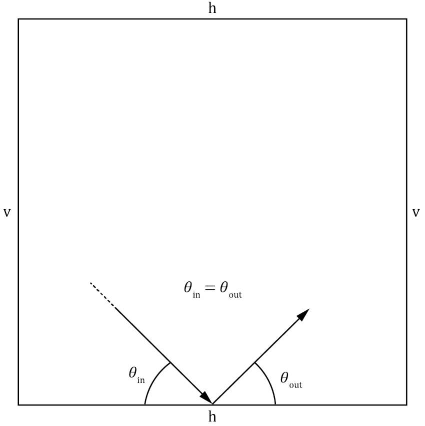
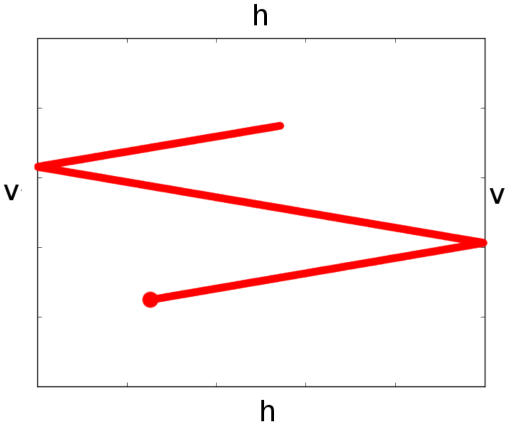
Introduction

Frictionless, massless, point-sized billiard ball bouncing in a square.



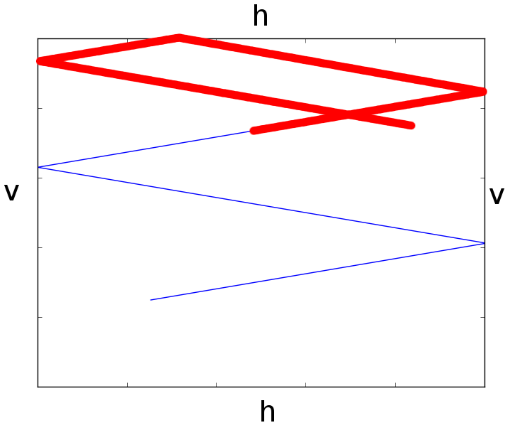
Example

vv



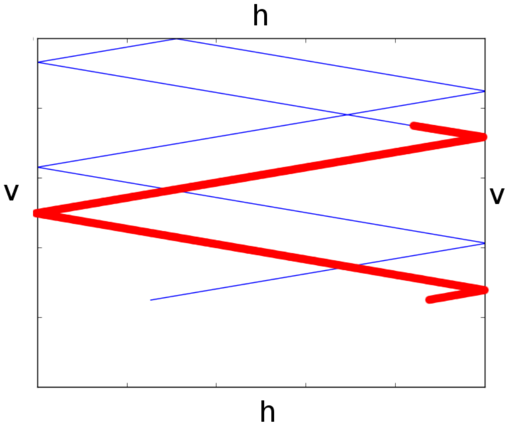
Example

$vv\,vhv$



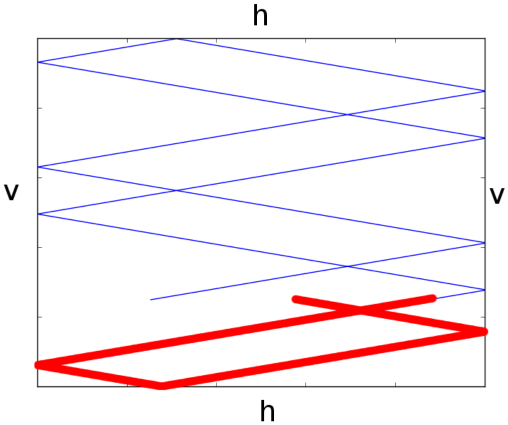
Example

vvvhvvvv



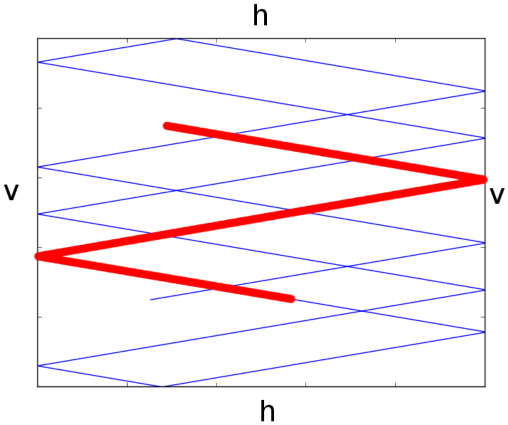
Example

vvvhvvvv *vhv*



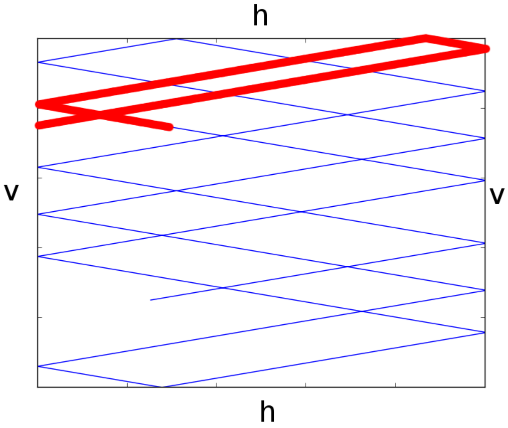
Example

$vvvhvvvvvhv\textcolor{red}{vv}$



Example

vvvhvvvvvhvvv *vhv*



Resulting Sequence

$$vvvhvvvvvhvvvvhv$$

Presentation Outline

Problem Statement

Problem: Given a sequence of v and h collisions, determine if it is a valid collision sequence.

Basic Notation

Definition

<u>v collision</u>: when the ball collides with a v side

Definition

<u>h collision</u>: when the ball collides with an h side

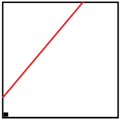
Definition

<u>Collision sequence (α)</u>: a sequence of v and h collisions which starts and ends with an h collision.

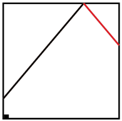
Tiling Representation

- Tile the table in the plane for a more powerful representation of the problem
- Tiling will reflect the table about each side
- After tiling, we only need to deal with straight line trajectories in a tiled plane

Tiling Tables



Tiling Tables



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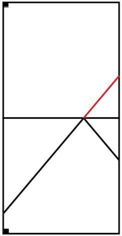

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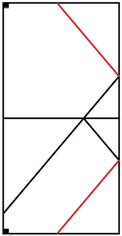

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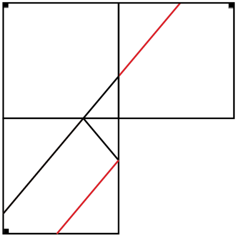

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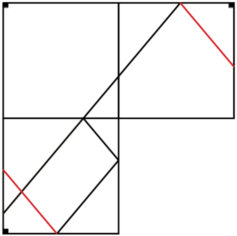

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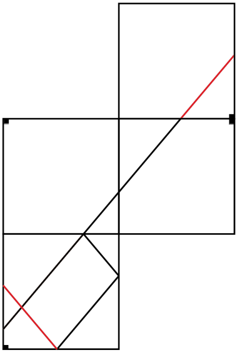

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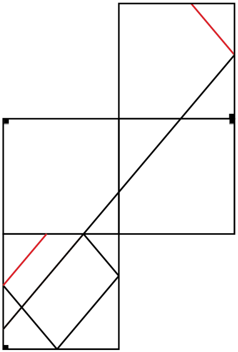

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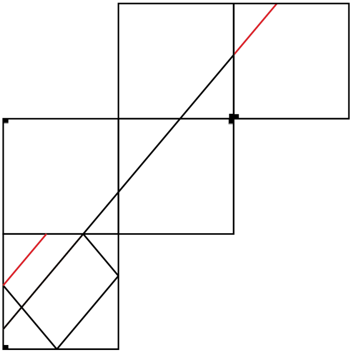

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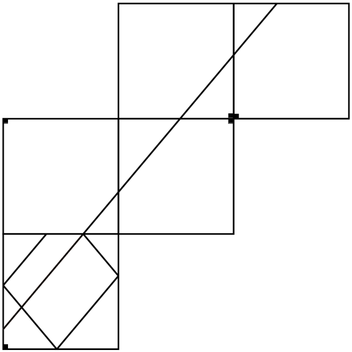

Indexing Definitions

$I(A, b)_k$: index of kth occurrence of b in A

β_i: # of v's between ith and (i+1)th h collisions: $[I(\alpha, h)]_{i+1} - [I(\alpha, h)]_i - 1$

Example

$$\alpha = hvvvvhvvvvhvvvh$$
$$I(\alpha, h) = (0, 5, 10, 14)$$
$$\beta = (4, 4, 3)$$

First Indexing Theorem

Theorem

$$\beta_i \geq 1 \qquad \forall\, i \in \{0, \ldots, \mathit{length}(I(\alpha, h)) - 2\}$$

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Example

- $\alpha = hvvhhvvvhvvhhvhhvvvvhvvvh \qquad \beta = (2, 0, 3, 2, 0, 1, 2, 4, 3)$
- $\alpha = hvvvvhvvvvhvhvvvhvvvvvvvh \qquad \beta = (4, 4, 1, 3, 7)$
- $\alpha = hvvvvhvvvvhvvvhvvvvhvvvvh \qquad \beta = (4, 4, 3, 4, 4)$

First Indexing Theorem

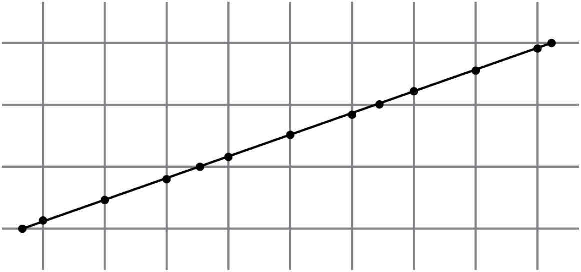
Theorem

$$\beta_i \geq 1 \qquad \forall\, i \in \{0, \ldots, length(I(\alpha, h)) - 2\}$$

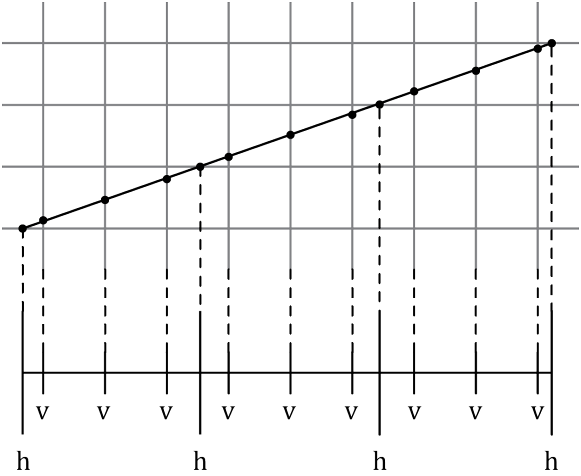
Example

- ~~$\alpha = hvvhhvvvhvvhhvhhvvvvhvvvh$ $\beta = (2, 0, 3, 2, 0, 1, 2, 4, 3)$~~
- $\alpha = hvvvvhvvvvhvhvvvhvvvvvvvh$ $\beta = (4, 4, 1, 3, 7)$
- $\alpha = hvvvvhvvvvhvvvhvvvvhvvvvh$ $\beta = (4, 4, 3, 4, 4)$

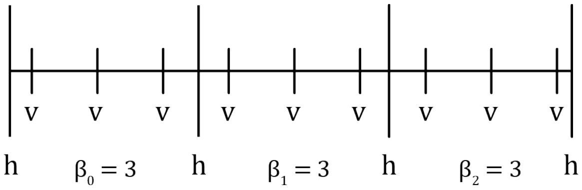
Parametric Representation



Parametric Representation



Parametric Representation



Second Indexing Theorem

Theorem

$$|\beta_i - \beta_j| \leq 1 \qquad \forall\ i, j \in \{0, \ldots, \mathit{length}(\beta) - 1\}$$

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Example

- $\alpha = hvvhhvvvhvvhhvhhvvvvhvvvh \qquad \beta = (2, 0, 3, 2, 0, 1, 2, 4, 3)$
- $\alpha = hvvvvhvvvvhvhvvvhvvvvvvvh \qquad \beta = (4, 4, 1, 3, 7)$
- $\alpha = hvvvvhvvvvhvvvhvvvvhvvvvh \qquad \beta = (4, 4, 3, 4, 4)$

Second Indexing Theorem

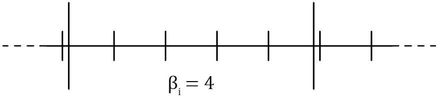
Theorem

$$|\beta_i - \beta_j| \leq 1 \qquad \forall\, i,j \in \{0,\ldots,length(\beta)-1\}$$

Example

- ~~$\alpha = hvvhhvvvhvvhhvhhvvvvhvvvh \qquad \beta = (2,0,3,2,0,1,2,4,3)$~~
- ~~$\alpha = hvvvvhvvvvhvhvvvhvvvvvvvh \qquad \beta = (4,4,1,3,7)$~~
- $\alpha = hvvvvhvvvvhvvvhvvvvhvvvvh \qquad \beta = (4,4,3,4,4)$

Windowing



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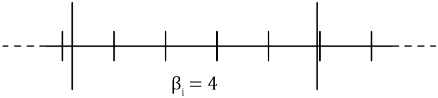

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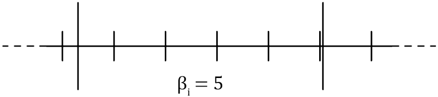

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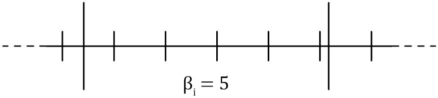

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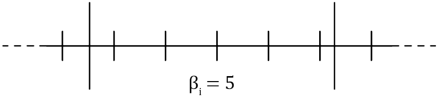

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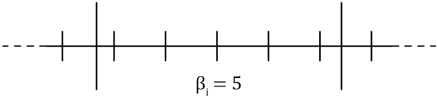

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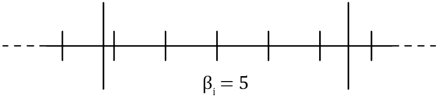

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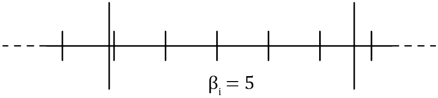

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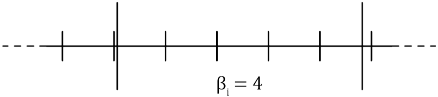

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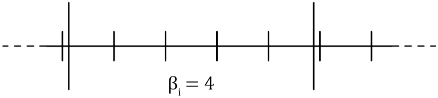

More Sub-Sequences

$$C_i^{(0)} := [I(\beta, \beta_{min})]_{i+1} - [I(\beta, \beta_{min})]_i \qquad \forall\ i \in \{0, \ldots, length(I(\beta, \beta_{min}) - 2)\}$$

More Sub-Sequences

$$C_i^{(0)} := [I(\beta, \beta_{min})]_{i+1} - [I(\beta, \beta_{min})]_i \quad \forall\ i \in \{0, \ldots, length(I(\beta, \beta_{min}) - 2)\}$$

$$C_i^{(j)} := [I(C_i^{(j-1)}, C_{min}^{(j-1)})]_{i+1} - [I(C_i^{(j-1)}, C_{min}^{(j-1)})]_i \quad \forall\ i \in \left\{0, \ldots, length(I(C_i^{(i-1)}, C_{min}^{(i-1)}) - 2)\right\}, \quad j \in \{0, N-1\}$$

where N is defined s.t.

$$\begin{cases} C^{(j)} \neq (1,) & \text{for } j < N-1 \\ C^{(j)} = (1,) & \text{for } j = N \end{cases}$$

Satisfiability Test (Fractal Version)

Theorem

A collision sequence is valid iff the following is true:

$$\beta_{max} - \beta_{min} \leq 1 \text{ and } C_{max}^{(j)} - C_{min}^{(j)} \leq 1 \qquad \forall\ j \in \{0, \ldots, N-1\}$$

Extensions to Cubes

- Assign x, y, and z as the opposite pairs of faces of a cube.
- Characterize sequences of x, y, and z collisions.

Intuition

- Examine collisions in xy, yz, and xz planes.
- Movement in each plane is independent.
- Combine xy, yz, and xz collision sequences to get final sequence.

Example

Example

xy sequence: $xxyyxx$

yz sequence: $zzyzyz$

xz sequence: $xxzzzx$