

# SEQUENCES OF BILLIARD BALL COLLISIONS

JONATHAN ALLEN, JOHN WANG

**Abstract.** In this paper we explore properties of sequences of billiard ball collisions. We present a tiling representation which is used to help elucidate some simple properties of these sequences. Then, we provide a one-dimensional representation which builds upon the tiling representation. Next, we provide a method which takes an arbitrary sequence and checks to see if it could have been created by a billiard ball colliding with a billiard table. Finally, we show how these sequences relate to continued fractions.

## 1. INTRODUCTION

In this paper we will explore sequences of billiard ball collisions. In particular, we look at the sequence of sides that a billiard ball collides with under perfect, frictionless conditions. We will show how a square billiard table can be analyzed by tiling the table in the plane, and prove a number of properties that billiard ball sequences must satisfy.

This introduction will explain the general setup of the problem and will give an example of how the definitions relate to a billiard ball with particular initial conditions.

**1.1. Setup.** We will imagine an infinitesimally small billiard ball on a square table. For simplicity, we will assume that the square table is defined on the unit square  $[0, 1]^2$ . The ball will start at some initial position  $\mathbf{x}_0$  inside of the table and with some velocity  $\mathbf{v}_0$ . We will assume that the ball is massless and frictionless, and that there is no gravity.

We will assume ideal, elastic collisions. To be more precise, when the ball collides with an edge of the table, the ball's velocity will be reflected across the line perpendicular to the edge of the table at the point of collision. In other words, the angle of incidence is equal to the angle of reflection on all billiard ball collisions. Figure 1 shows the general mechanics of a collision.

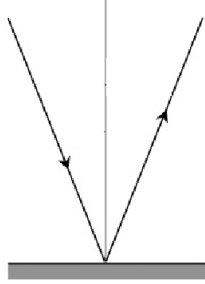


FIGURE 1. Mechanics of a Billiard Ball Colliding with a Table Edge

Now, we will label the horizontal sides of the table  $h$  and the vertical sides of the table  $v$ . Whenever the billiard ball collides with a horizontal side (labelled  $h$ ), we will call the resulting collision an  $h$ -collision. Whenever the ball collides with a vertical side (labelled  $v$ ), we will call the resulting collision a  $v$ -collision.

We will now define what this paper will be primarily interested in, a sequence of collisions:

**Definition 1.1.** *A collision sequence  $(\alpha)$  for a ball  $B$  is the sequence of  $v$ 's and  $h$ 's which appear as the ball collides with the walls of the billiard table.*

Notice that all non-trivial initial conditions for a billiard ball will result in infinitely many  $h$ -collisions. The only initial conditions for which this is not true are when the initial velocity is parallel to the horizontal (for example when  $\mathbf{v}_0 = (1, 0)$ ) so that the ball bounces infinitely between the two vertical sides. The proof of this is trivial and should become clear once the tiling representation is presented, so we will omit it.

Thus, it is perfectly reasonable to constrain a ball's collision sequence to begin and end with an  $h$  collision, since one simply needs to extend the number of collisions one watches until the sequence of collisions begins and ends with an  $h$ -collision. This constraint will later make it easier to reason about properties of sequences.

**1.2. Example Collision Sequence.** To understand collision sequences better, we will provide an example. Consider a billiard ball with initial position  $\mathbf{x}_0 = (0.75, 0.75)$  and initial velocity  $\mathbf{v}_0 = (0.23, 0.05)$ .

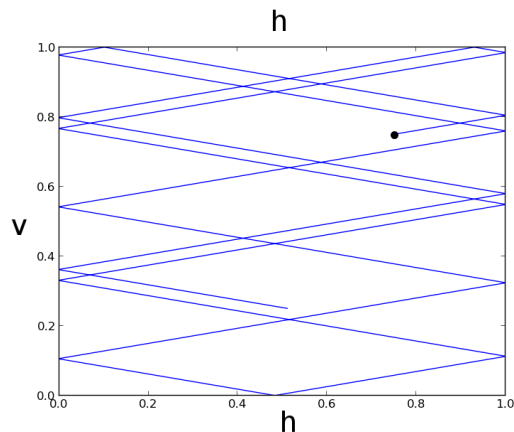


FIGURE 2. Example Billiard Ball Trajectory,  $x_0 = (0.75, 0.75)$ ,  $v_0 = (0.23, 0.05)$

We can see from the figure that the collisions that it makes, denoting a  $v$ -collision with a  $v$  and an  $h$ -collision with an  $h$ , are:

$$(1) \quad (v, h, v, v, v, v, v, h, v, v, v, v, v, h, v, v, v)$$

A valid collision sequence given these initial conditions would start and end with an  $h$  collision. A possible example would be:

$$(2) \quad \alpha = hvvvvvvhvvvvvh$$

Notice that the collisions will continue infinitely, so one could imagine extending this collision sequence to include more  $v$  and  $h$  collisions. Although not shown in the picture, the following collision sequence would also be valid if one continued showing the trajectory of the ball in future collisions:

$$(3) \quad \alpha = hvvvvvvhvvvvvhvvvvvh$$

**1.3. Simplifications.** There are some simplifications that we can make which will make talking about billiard balls, their initial conditions, and their collision sequences easier.

- We can change the magnitude of the initial velocity  $\mathbf{v}_0$  without changing any collision sequences. This is because only the direction of  $\mathbf{v}_0$  affects the points of collision of the billiard ball with the table. Thus, the only part of the initial velocity that we care about is the velocity's direction. Thus, we can characterize  $\mathbf{v}_0$  by the angle  $\gamma$  that  $\mathbf{v}_0$  makes with the positive horizontal line

(just as in polar coordinates). From now on, we will use  $\mathbf{v}_0$  and  $\gamma$  interchangeably.

- We can constrain the initial velocity's angle to the range  $\gamma \in [0, \pi/2]$ . This is because any initial velocity in the range  $\gamma \in [-\pi/2, \pi/2]$  will create equivalent collision sequences as  $\pi + \gamma \in [0, \pi/2]$  (this will be clear once we present the tiling representation later in the paper). Moreover, any angle in the range  $\gamma \in [0, \pi/2]$  will create equivalent collision sequences as those in  $[-\pi/2, 0]$  by simply reflecting the cube about one of its horizontal sides. For the rest of the paper, we will assume  $\gamma \in [0, \pi/2]$ .

## 2. TILING REPRESENTATION

We will now present a representation of the problem which will greatly simplify the analysis of  $v$  and  $h$  collisions for some ball  $B$ , called the tiling representation. First we will define some basic definitions.

**Definition 2.1.** *A billiard ball trajectory  $\tau(t_0, t_1)$  is the curved traced by a billiard ball  $B$  between times  $t_0$  and  $t_1$ .*

**Definition 2.2.** *A collision time  $\kappa_i$  for a billiard ball  $B$  is the time at which the  $i$ th collision occurs.*

To understand the basics of how the tiling representation works, imagine placing a unit square billiard table on the  $xy$  plane  $([0, 1]^2)$ . The table's edges will be the four line segments bordering the unit square. A ball will start with some initial position  $\mathbf{x}_0 \in [0, 1]^2$  and velocity  $\mathbf{v}_0$ . After some time, the ball will collide with an edge  $e_0$  of the table at time  $\kappa_1$ . However, instead of thinking of the trajectory of the ball as being reflected across the line perpendicular to  $e_0$  at the point of collision, we will instead reflect the original unit square  $s_0$  across the edge  $e_0$  to create a new square  $s_1$ . Now, the trajectory  $\tau(\kappa_1, \kappa_2)$  of the ball after the first collision will be traced in the new square  $s_1$ .

In other words, the trajectory  $\tau(0, \kappa_1)$  before the first collision will be confined to the original square  $s_0$ , and the trajectory  $\tau(\kappa_1, \kappa_2)$  after the first collision will be confined to the new reflected square  $s_1$ . We can continue the process for each new collision. Suppose the ball collides with edge  $e_1$  in square  $s_1$ . Then, we will create a new square  $s_2$  which is a reflection of square  $s_1$  across the edge  $e_1$ . The trajectory of the ball  $\tau(\kappa_2, \kappa_3)$  after the second collision will be confined to the newest reflected square  $s_2$ . This process will continue on indefinitely so that the trajectory  $\tau(\kappa_j, \kappa_{j+1})$  will be confined to the square  $s_j$ , where square

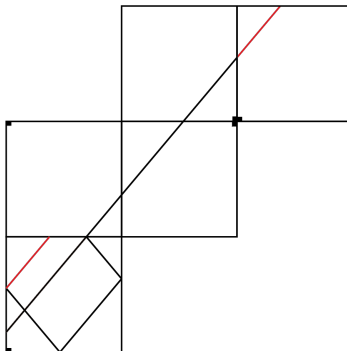


FIGURE 3. Example of Tiling Billiard Tables

$s_{j+1}$  is generated by reflecting square  $s_j$  across the edge  $e_j$  which is collided with at time  $\kappa_j$ .

Figure 3 shows an example trajectory which is created using this tiling process. In essence, the tiling representation reflects a table about each of its four sides. These reflections will perform the same process, eventually tiling and completely filling the  $xy$  plane. The trajectory of particular billiard ball can then be traced through the tiling in the  $xy$ -plane, as seen in figure 3.

A couple of interesting observations can be made:

- The combined trajectory  $T = \{\tau(0, \kappa_1), \tau(\kappa_1, \kappa_2), \tau(\kappa_2, \kappa_3), \dots\}$  of a ball creates a ray in the  $xy$  plane.
- All  $v$ -collisions happen exactly when the combined trajectory  $T$  intersects with the integer vertical lines  $x = k$  where  $k \in \mathbb{Z}$ . The same can be said of  $h$ -collisions and integer horizontal lines  $y = k$  for  $k \in \mathbb{Z}$ .

We can formalize and prove each of these observations in turn:

**Theorem 2.3.** *The combined trajectory  $T = \{\tau(0, \kappa_1), \tau(\kappa_1, \kappa_2), \dots\}$  of a billiard ball is a ray in the  $xy$  plane under the tiling representation.*

*Proof.* We need to show that all trajectories  $\tau(0, \kappa_1), \tau(\kappa_1, \kappa_2), \dots$  which constitute the combined trajectory lie on a single line. We know that trajectories  $\tau(\kappa_i, \kappa_{i+1})$  are line segments because the velocity of the

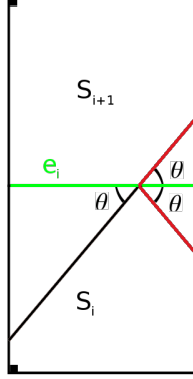


FIGURE 4. Trajectories  $\tau(\kappa_{i-1}, \kappa_i)$  in  $s_i$  and  $\tau(\kappa_i, \kappa_{i+1})$  in  $s_{i+1}$  forming a line segment

billiard ball only changes during a collision. Thus, we just need to show that each trajectory  $\tau(\kappa_i, \kappa_{i+1})$  lies on the same line, i.e. that  $\tau(\kappa_i, \kappa_{i+2})$  is a line segment for all  $i \in \mathbb{Z}$ .

We will show this by analyzing the change in trajectory at time  $\kappa_i$ . We know that at any time  $t \in (\kappa_{i-1}, \kappa_i)$ , the billiard ball will be on the line segment defined by the trajectory  $\tau(\kappa_{i-1}, \kappa_i)$ . This trajectory makes an angle  $\theta$  with the edge  $e_i$  which the billiard ball collides with at time  $\kappa_i$ . Moreover, we know that after colliding with  $e_i$ , the angle of reflection of the trajectory is equal to the angle of incidence  $\theta$  by our definition of collision.

The velocity is reflected about the line perpendicular to  $e_i$  at the point of collision, but the angle that the trajectory  $\tau(\kappa_i, \kappa_{i+1})$  makes with  $e_i$  remains the same. Thus, when square  $s_i$  is reflected about  $e_i$ , the resulting trajectory in  $s_{i+1}$  makes an angle of  $\theta$  with  $e_i$ . Figure 4 shows this process graphically.

It is clear that the angles that  $\tau(\kappa_{i-1}, \kappa_i)$  and  $\tau(\kappa_i, \kappa_{i+1})$  make with  $e_i$  are both  $\theta$ . Since both of these trajectories are already line segments, we see that the union of the two trajectories is also a line segment because both trajectories lie on the same line. Thus, we see that all trajectories  $\tau(\kappa_j, \kappa_{j+1})$  for all  $j \in \mathbb{Z}$  lie on the same line, which completes the proof.  $\square$

**Theorem 2.4.** *Let  $t_{v,k}$  be a time when the combined trajectory  $T$  intersects with some integer vertical line  $x = k$  where  $k \in \mathbb{Z}$ . We must have  $\kappa_k^v = t_{v,k}$ , where  $\kappa_k^v$  is the time at which the  $k$ th  $v$ -collision occurs.*

Similarly, let  $t_{h,k}$  be a time when the combined trajectory  $T$  intersects with some horizontal vertical line  $y = k$  for  $k \in \mathbb{Z}$ . Then,  $\kappa_k^h = t_{h,k}$ .

*Proof.* The proof of the first statement is exactly analogous to the proof of the second statement, so we will only prove the theorem for  $\kappa_k^v = t_v$ .

Recall that in the tiling representation, whenever the billiard ball collides with an edge  $e_j$ , a new square  $s_{j+1}$  gets reflected across  $e_j$ . It is clear that  $e_j$ , if it is a horizontal edge, lies on some integer horizontal line  $y = c$  where  $c \in \mathbb{Z}$ . Alternatively, if  $e_j$  is a vertical edge then it lies on some integer vertical line  $x = c$  where  $c \in \mathbb{Z}$ . Thus each  $\kappa_j$  corresponds to when the combined trajectory  $T$  intersects with some integer vertical or integer horizontal line.

It is also clear that the billiard ball cannot make a  $v$ -collision at time  $t$  unless the combined trajectory  $T$  intersects with an integer vertical line at time  $t$  as well. Therefore, we see that  $v$ -collisions occur exactly when  $T$  intersects with an integer vertical line.

We know that  $T$  traces a ray in the  $xy$  plane by theorem 2.3. By assumption, this ray starts in the unit square  $[0, 1]^2$  and has an angle between 0 and  $\pi/2$  with the horizontal. Thus, the first  $v$ -collision occurs when  $T$  intersects  $x = 1$ , the second  $v$ -collision occurs when  $T$  intersects  $x = 2$ , and the  $k$ th  $v$ -collision occurs when  $T$  intersects  $x = k$ .

However, we know that the  $k$ th  $v$ -collision occurs at time  $\kappa_k^v$  by definition, and that the  $t_{v,k}$  is the time when  $T$  intersects with  $x = k$ . Therefore, we see that  $\kappa_k^v = t_{v,k}$ .  $\square$

We now see that we can represent the combined trajectory  $T$  of a billiard ball as a ray in the plane. We can define the line which the ray lies on as  $y = mx + y_0$ , where  $m$  is the slope of the line and is given by  $m = \frac{\mathbf{v}_y}{\mathbf{v}_x}$  and  $y_0$  is the  $y$ -intercept which can be determined by  $\mathbf{x}_0$  by solving for  $\mathbf{x}_y = m\mathbf{x}_x + y_0$ . This line represents the entire combined trajectory, and also determines all possible collision sequences for a particular billiard ball, since  $v$ -collisions happen when  $x$  is an integer and  $h$ -collisions happen when  $y$  is an integer.

Thus, we see that the  $i$ th  $v$ -collision occurs when  $y = mi + y_0$  and the  $i$ th  $h$ -collision occurs when  $x = (i - y_0)/m$ .

### 3. SIMPLE PROPERTIES

We will now use the tiling representation that we have developed to discover properties of collision sequences. The first simple property is that collision sequences are periodic when the initial conditions are rational numbers. Now that we can define a billiard ball as a line,

instead of giving initial conditions  $\mathbf{x}_0$  and  $\mathbf{v}_0$ , we can give the slope  $m$  and the  $y$ -intercept  $y_0$  of the complete trajectory's line. The formalized theorem is then:

**Theorem 3.1.** *There exists a  $k \in \mathbb{N}$  such that  $y_0 \equiv mk + y_0 \pmod{2}$  if and only if  $m \in \mathbb{Q}$ .*

*Proof.* Let us first show that if  $m \in \mathbb{Q}$ , then there exists a  $k \in \mathbb{N}$  such that  $y_0 \equiv mk + y_0 \pmod{2}$ . We simply need to show that  $0 \equiv mk \pmod{2}$  if  $m \in \mathbb{Q}$ . However, since we know  $m \in \mathbb{Q}$ , we can decompose it as follows  $m = p/q$  where  $p, q \in \mathbb{Z}$ . Thus, we have  $mk \pmod{2} \equiv \frac{pk}{q} \pmod{2}$ . Now we can choose:

$$(4) \quad k = \begin{cases} q & \text{if } p \pmod{2} \equiv 0 \\ 2q & \text{if } p \pmod{2} \equiv 1 \end{cases}$$

In this way, we see that  $0 \equiv \frac{pk}{q} \pmod{2}$ , which proves the first half of the theorem.

Now let us show that if there exists a  $k \in \mathbb{N}$  such that  $y_0 \equiv mk + y_0 \pmod{2}$ , then  $m \in \mathbb{Q}$ . If such a  $k$  exists, then we must have  $0 \equiv mk \pmod{2}$ , which means that  $mk = 2q$  for some  $q \in \mathbb{Z}$ . This means  $m = \frac{2q}{k}$ . Now it is clear that  $m \in \mathbb{Q}$  because both its numerator and denominator are integers.  $\square$

Theorem 3.1 shows that if  $m \in \mathbb{Q}$ , then the billiard ball will eventually return to its original position  $\mathbf{x}_0$  with its original velocity  $\mathbf{v}_0$ . Seeing why this is true is just a matter of using the tiling representation. We note that every second square in either the  $x$  or  $y$  direction is the same (because of the transitivity of reflection). Therefore, every second square will have a trajectory that exactly corresponds to the trajectory in the original square.

Thus, if  $y_0 \equiv mk + y_0 \pmod{2}$ , then the  $y$ -intercept from one of the secondary squares is the same as the  $y$ -intercept from the original square. Since we know that the secondary squares have the same trajectories as in the original square, we see that the trajectory will have returned to its original position (since the velocity is the same). Thus, if  $y_0 \equiv mk + y_0 \pmod{2}$ , then we know that the billiard ball will return to its original position with its original velocity. Theorem 3.1 also shows that if  $m$  is irrational, then the billiard ball will never return to its original position and velocity.

We can also examine consecutive occurrences of  $v$  and  $h$ . For example, can we have consecutive occurrences of both  $v$  and  $h$  like in the sequence  $hhvvhh$ ? In fact, we cannot as theorem 3.2 shows.



**Theorem 3.2.** *A valid collision sequence cannot have both consecutive occurrences of  $v$  and consecutive occurrences of  $h$ .*

*Proof.* We have already shown in theorem 2.3 that the combined trajectory of a billiard ball must be a ray. This ray must lie on some line with some slope  $m \in \mathbb{R}$  or with undefined slope (when the line is vertical). When the line is vertical, it is clear that the theorem holds, because only  $v$  collisions occur.

There are two cases left:  $|m| < 1$  or  $|m| \geq 1$ . If  $|m| \geq 1$ , then the number of  $v$ -collisions between the  $x$ th and the  $x + 1$ st  $h$ -collision will be  $\lfloor (m(x+1) + y_0) - (mx + y_0) \rfloor = \lfloor m \rfloor \geq 1$ . Thus, we see that for any  $x \in \mathbb{N}$ , we must have at least 1  $v$ -collision between the  $x$ th and  $x + 1$ st  $h$ -collisions, which proves the theorem for  $|m| \geq 1$ .

If  $|m| < 1$ , then the number of  $h$ -collisions between the  $y$ th and  $y + 1$ st  $v$ -collisions will be  $\lfloor ((y+1) - y_0)/m - (y - y_0)/m \rfloor = \lfloor 1/m \rfloor > 1$ . This shows that there will be at least 1  $h$ -collision between the  $y$ th and  $y + 1$ st  $v$ -collisions for all  $y \in \mathbb{N}$ . This completes the theorem.  $\square$

We therefore see that if  $v$  occurs consecutively in a collision sequence, then  $h$  cannot occur consecutively and vice versa. For example, the sequence  $hvvhh$  has two consecutive occurrences of  $v$  and two consecutive occurrences of  $h$ , so it cannot be a valid collision sequence. However, the sequence  $hvvhvvvh$  does not have consecutive occurrences of  $h$ , so theorem 3.2 does not rule it out as a valid collision sequence.

Theorem 3.2 allows us to make a simplification for our collision sequences. Since one of either  $v$  or  $h$  must occur non-consecutively, we can arbitrarily assign  $v$  to be the side that occurs non-consecutively by rotating the billiard table and creating the opposite collision sequence. For example, the sequence  $vhhhvhhh$  is the same as the sequence  $hvvvhvvvh$  when one rotates the billiard table by  $\pi/2$ . Therefore, from now on, we can confine all our sequences to have only non-consecutive occurrences of  $v$  (i.e. sequences like  $hvvvhvvvh$  become  $vhhhvhhh$ ) without loss of generality.

#### 4. 1-DIMENSIONAL REPRESENTATION

Rather than looking at the explicit representation equation of lines in the plane, we can gain much more insight from looking at the parametric representation. To simplify our analysis, we will choose our time parameter such that  $v$  collisions occur every  $\Delta t = 1$  and  $h$  collisions occur every  $\Delta t = m$ . The equation for a line  $y(x) = mx + y_0$  is equivalent to the following parametric system

$$(5) \quad x_0 := -\frac{y_0}{m}$$

$$(6) \quad x(t) = \frac{1}{m}t + x_0$$

$$(7) \quad y(t) = t$$

Now v and h collisions in the 2-dimensional plane can be projected onto the 1-dimensional  $t$  axis. The problem of mapping collision sequences to lines in the plane becomes a problem of fitting tick marks with regular spacing 1 into intervals of length  $m$ .

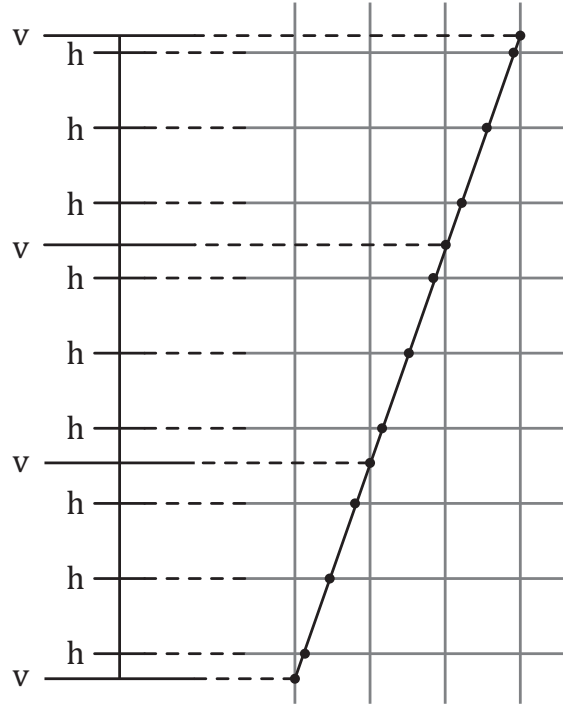


FIGURE 5. Projecting onto the parametric representation.

For the sake of space, we will rotate the  $t$  axis so that it is horizontal.

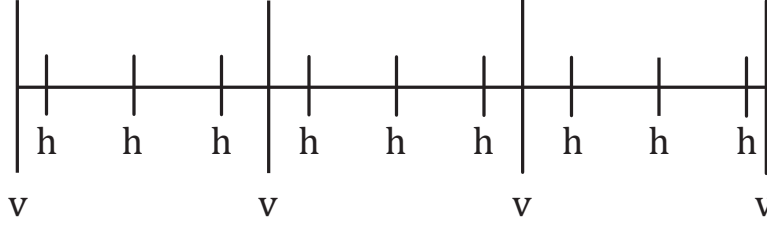


FIGURE 6. An example collision sequence.

**Lemma 4.1.** *Let  $l_2 < l_1$ . The number of real numbers at regular spacing  $l_2$  inside an open interval of length  $l_1$  is in  $\left\{ \left\lfloor \frac{l_1}{l_2} \right\rfloor, \left\lceil \frac{l_1}{l_2} \right\rceil \right\}$ .*

*Proof.* Let  $A \subset \mathbb{Z}$  represent the set of all possible numbers of real numbers at regular spacing  $l_2$  inside an open interval of length  $l_1$ . Given some  $a \in A$ , let  $b \in \mathbb{R}$  be defined such that the following holds

$$(8) \quad l_1 = (a - 1)l_2 + b$$

We know that  $(a - 1)l_2 < l_1$ , so  $b \geq 0$ . Also,  $b < 2l_2$  because otherwise, there must be more than  $a$  real numbers inside the interval, contradicting our original assumption.

Rearranging Equation 8, we get

$$(9) \quad a = \frac{l_1}{l_2} + 1 - \frac{b}{l_2}$$

$$(10) \quad \frac{l_1}{l_2} - 1 < a < \frac{l_1}{l_2} + 1$$

$$(11) \quad a \in \left\{ \left\lfloor \frac{l_1}{l_2} \right\rfloor, \left\lceil \frac{l_1}{l_2} \right\rceil \right\}$$

□

## 5. THE $\beta$ GROUP

Before continuing, we need to take a tangent and develop a group of sequences which we will call the  $\beta$  group, that will be very useful for developing validation conditions on a collision sequence. The first sequence in this group is defined below.

**Definition 5.1.** *Given a collision sequence  $\alpha$ , define a sequence  $\beta^{(0)}$  where each element  $\beta_i^{(0)}$  is the number of  $h$ 's between the  $i^{th}$  and  $(i+1)^{th}$*

$v$  in  $\alpha$ . From Lemma 4.1, each element in  $\beta^{(0)}$  can be one of two different values, which we will refer to as  $\beta_{\min}^{(0)}, \beta_{\max}^{(0)}$ .

Graphically,  $\beta_i^{(0)}$  represents the number of tick marks in each interval. An example sequence is shown in Figure 7.

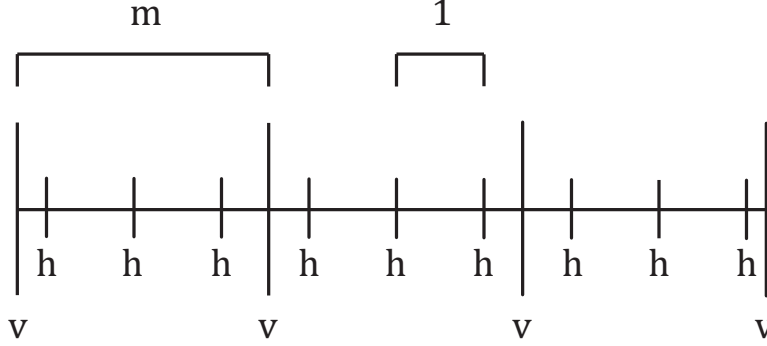


FIGURE 7. An example  $\beta^{(0)}$  visual representation.

We will the rest of the sequences in the  $\beta$  group inductively.

**Definition 5.2.** Given a  $j > 0$  and a collision sequence  $\alpha$ , assume that  $\beta^{(j-1)}$  is defined and each element in the sequence is either  $\beta_{\min}^{(j-1)}$  or  $\beta_{\max}^{(j-1)}$ . The sequence  $\beta^{(j)}$  is defined such that each element  $\beta_i^{(j)}$  is 1 more than the number of occurrences of  $\beta_{\max}^{(j-1)}$  between the  $i^{\text{th}}$  and  $(i+1)^{\text{th}}$  occurrence of  $\beta_{\min}^{(j-1)}$  in the  $\beta^{(j-1)}$  sequence. From Lemma 4.1, each element in  $\beta^{(j)}$  can be one of two different values, which we will refer to as  $\beta_{\min}^{(j)}, \beta_{\max}^{(j)}$ .

If, for some  $j_f$ , the length of  $\beta^{(j_f-1)}$  is 1, then  $\beta^{(j_f-1)}$  is called the terminating  $\beta$  sequence, and all subsequent  $\beta^{(j)}$  for  $j \geq j_f$  are undefined.

$\beta^{(j)}$  is much simpler to understand visually. A visualization representation is formed using the following rules:

- (1) Divide the number line into regular intervals of length  $a_j$ .
- (2)  $\beta_{\min}^{(j-1)}$  are represented as tick marks on the number line with a regular spacing  $a_{j+1}$ .
- (3) There is exactly one  $\beta_{\min}^{(j-1)}$  tick mark in each interval.
- (4) In each interval, all the  $\beta_{\max}^{(j-1)}$  terms come before the  $\beta_{\min}^{(j-1)}$  term.

Then  $\beta_i^{(j)}$  is the number of tick marks in each interval. An example  $\beta^{(j-1)}$  visual representation is shown in Figure 8.

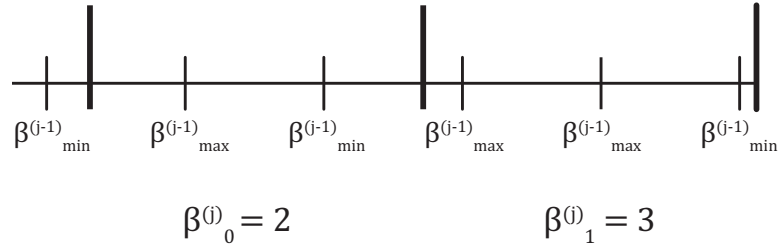


FIGURE 8. An example  $\beta^{(j)}$  visual representation.

Lastly, we will need a new sequence  $\delta^{(j)}$  where each element  $\delta_i^{(j)}$  is the distance between the  $(i \beta_{max}^{(j)})^{th}$  tick mark and the beginning of the  $i^{th}$  interval in the  $\beta^{(j)}$  visual representation. We also include an offset  $x_0$  for reasons that will become clear shortly.

**Definition 5.3.**  $\delta^{(j)}$  is defined more precisely as

$$(12) \quad \delta_i^{(j)} := \begin{cases} x_0 & \text{for } i = 0 \\ i(\beta_{max}^{(j)} * a_{j-1} - a_{j-2}) + x_0 & \text{for } i \geq 1 \end{cases}$$

An example  $\beta^{(j)}$  sequence is plotted in 9, with the  $\delta^{(j)}$  values indicated and every  $(\beta_{max}^{(j)})^{th}$  tick mark highlighted in red.

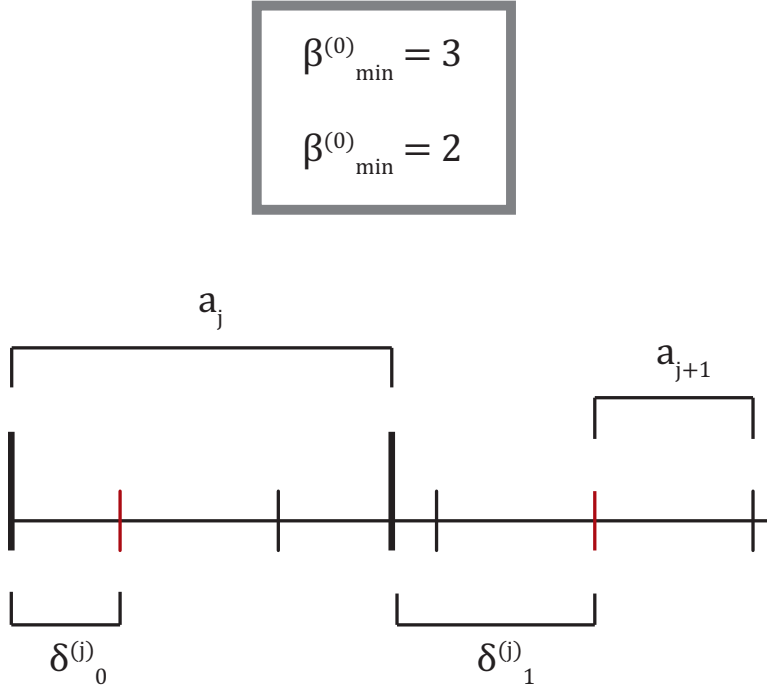


FIGURE 9. Example collision sequence with every  $(\beta_{\max}^{(0)})^{th}$  tick mark highlighted in red.

The number of tick marks in the  $i^{th}$  interval is thus equal to  $\beta_{\max}^{(j)}$  plus the number of tick marks included in the  $\delta_i^{(j)}$  interval minus the number of tick marks included in the  $\delta_{i+1}^{(j)}$  interval. More precisely

$$(13) \quad \beta_i^{(j)} = \lfloor \delta_i^{(j)} \rfloor + \beta_{\max}^{(j)} - \lfloor \delta_{i+1}^{(j)} \rfloor$$

## 6. SATISFIABILITY CONDITIONS

**Lemma 6.1.** *A finite sequence  $\alpha$  is a valid collision sequence iff there exists at least one valid collision sequence containing  $\alpha$  that starts and ends with an  $h$ .*

*Proof.* TODO: can extend any collision sequence to any length.  $\square$

Because of Lemma 6.1, without loss of generality we can confine ourselves to only look at collision sequences that start and end with an  $h$ .

We will now show how the sequences in the  $\beta$  group relate to the original problem of validating a collision sequence. In the process we will generate the sequence of interval sizes  $a$ .

**TODO: still trying to figure out how to explain how the  $\beta$  sequences relate to the original problem**

We start with  $a_0 := m, a_1 := 1$ , which are the spacing of  $v$  collisions and  $h$  collisions respectively in the parametric representation. The rest of the  $a$  sequence is generated inductively.

For some  $2 \leq j < j_f$ , assume that  $a_{j-1}, a_{j-2}$  exist.

$$(14) \quad a_j = \beta_{max}^{(j-2)} a_{j-1} - a_{j-2} \quad \text{for } 2 \leq j < j_f$$

From now on we will only consider collision sequences, where each non-terminal  $\beta^{(j)}$  starts and ends with  $\beta_{min}^{(j)}$ .

**Theorem 6.2.** *A collision sequence is valid if the following is true for all  $j$*

$$(15) \quad \beta_i^{(j)} \in \left\{ \left\lfloor \frac{a_{j-2}}{a_{j-1}} \right\rfloor, \left\lceil \frac{a_{j-2}}{a_{j-1}} \right\rceil \right\}$$

*Proof.* This follows directly from Lemma 4.1 and the definition of  $\beta^{(j)}$ .  $\square$

**Theorem 6.3.** *For every valid collision sequence,  $\lim_{n \rightarrow \infty} a_n = 0$*

*Proof.* From the definition of  $a_j$

$$(16) \quad a_j = \beta_{max}^{(j-2)} a_{j-1} - a_{j-2}$$

$$(17) \quad = \left\lceil \frac{a_{j-2}}{a_{j-1}} \right\rceil a_{j-1} - a_{j-2}$$

Now from the definition of the ceiling function, we know that

$$(18) \quad 0 \leq \left\lceil \frac{a_{j-2}}{a_{j-1}} \right\rceil - \frac{a_{j-2}}{a_{j-1}} < 1$$

Rearranging, we get

$$(19) \quad 0 \leq \left\lceil \frac{a_{j-2}}{a_{j-1}} \right\rceil a_{j-1} - a_{j-2} < a_{j-1}$$

Combining the above equation with Equation 16, we get

$$(20) \quad 0 \leq a_j < a_{j-1}$$

Thus  $a$  is strictly decreasing and bounded below by 0, so  $\lim_{n \rightarrow \infty} a_n = 0$ .  $\square$

### 6.1. Continued fractions (Jon's Notes).

$$(21) \quad a_0 = m$$

$$(22) \quad a_1 = 1$$

$$(23) \quad a_2 = \beta_{max}^{(0)} - m$$

$$(24) \quad a_3 = \beta_{max}^{(1)} (\beta_{max}^{(0)} - m) - 1$$

$$(25) \quad a_4 = \beta_{max}^{(2)} (\beta_{max}^{(1)} (\beta_{max}^{(0)} - m) - 1) - (\beta_{max}^{(0)} - m)$$

$$(26) \quad a_0 \approx 0 \quad \rightarrow \quad m \approx 0$$

$$(27) \quad a_1 \approx 0 \quad \rightarrow \quad m \approx 1$$

$$(28) \quad a_2 \approx 0 \quad \rightarrow \quad m \approx \beta_{max}^{(0)}$$

$$(29) \quad a_3 \approx 0 \quad \rightarrow \quad m \approx \beta_{max}^{(0)} - \frac{1}{\beta_{max}^{(1)}}$$

$$(30) \quad a_4 \approx 0 \quad \rightarrow \quad m \approx \beta_{max}^{(0)} - \frac{1}{\beta_{max}^{(1)} - \frac{1}{\beta_{max}^{(2)}}}$$

## 7. CONTINUED FRACTIONS

Finally, we will show how collision sequences relate to continued fractions. Recall that a continued fraction is an expression of any real number as a sum of an integer part and the reciprocal of another number. For example,  $r \in \mathbb{R}$  can be represented as follows:

$$(31) \quad r = k_1 + \frac{1}{k_2 + \frac{1}{k_3 + \dots}}$$

$$(32)$$

Integers  $k_1, k_2, \dots$  are called quotients of the continued fraction. A real number  $r$  can be expressed in its continued fraction form  $r = [k_1, k_2, k_3, \dots]$ . The quotient  $k_i$  is found by taking the reciprocal of the fractional part of  $k_{i-1}$  (setting  $k_0 = r$ ).



If use the continued fraction representation for the slope  $m$  of a combined trajectory for a billiard ball, then we have:

$$(33) \quad m = \lfloor m \rfloor + \frac{1}{\lfloor 1/\{m\} \rfloor + \frac{1}{\lfloor 1/\{1/\{m\}\} \rfloor + \dots}}$$

Where the quotients are given by:

$$(34) \quad k_1 = \lfloor m \rfloor$$

$$(35) \quad k_2 = \left\lfloor \frac{1}{\{m\}} \right\rfloor$$

$$(36) \quad k_3 = \left\lfloor \frac{1}{\left\{ \frac{1}{\{m\}} \right\}} \right\rfloor$$

$$(37) \quad k_4 = \left\lfloor \frac{1}{\left\{ \frac{1}{\left\{ \frac{1}{\{m\}} \right\}} \right\}} \right\rfloor$$

$$(38) \quad \vdots$$

$$(39)$$

We see that the quotients are given by the recursive formula:  $k_j = \left\lfloor \frac{1}{m - k_{j-1}} \right\rfloor$ . In fact, a more interesting observation is that the sequence of quotients  $k_j$  form exactly the sequence of the minimum number of tick marks in each  $\beta^{(j)}$  subproblem:

**Theorem 7.1.** *Given the continued fraction representation  $m = [k_1, k_2, k_3, \dots]$  for the slope  $m \in \mathbb{R}$  of the combined trajectory  $T$  of a billiard ball, we must have  $k_j = \beta_{min}^{(j)}$ .*

*Proof.* We will proceed by induction. This is clearly true for  $k_1 = \lfloor m \rfloor$  by lemma 4.1, since for  $\beta_{min}^{(j)}$  the spacing of the larger tick marks are  $m$  and the spacing of the smaller tick marks is 1.

Now suppose we have shown our hypothesis to be true for  $k_{j-1}$ . This means that  $\beta_{min}^{(j-1)} = k_{j-1}$ . By definition ?? (of the sequence  $\beta^{(j)}$ ), we see that  $\beta_i^{(j)}$  is one more than the number of occurrences of  $\beta_{max}^{(j-1)}$  between the  $i$ th and  $(i+1)$ st occurrence of  $\beta_{min}^{(j-1)}$  in the  $\beta^{(j-1)}$  sequence.  $\square$

In fact, one can see that the process of finding  $\beta_i^{(j)}$  for the  $\beta^{(j)}$  subproblems exactly mirrors the process of finding the quotients  $k_j$  in a continued fraction of  $m$ .

## 8. CONCLUSION

TODO