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ABSTRACT

We consider the outer billiard outside a regular convex polygon. We deal with the case of regular polygons with 3, 4, 5, 6 or 10 sides. We describe the symbolic dynamics of the map and compute the complexity of the language.

Keywords: Symbolic dynamic, outer billiard, complexity function, words.
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1 Introduction

An outer billiard table is a compact convex domain $P$. Pick a point $M$ outside $P$. There are two half-lines starting from $M$ tangent to $P$, choose one of them, say the one to the right from the view-point of $M$, and reflect $M$ with respect to the tangency point. One obtains a new point, $N$, and the transformation $T : TM = N$ is the outer (a.k.a. dual) billiard map, see Figure 1. The map $T$ is not defined if the support line has a segment in common with the outer billiard table. In the case where $P$ is a convex polygon the tangency points are vertices of $P$. The set of points for which $T$ or any of its iterations is not defined is contained in a countable union of lines and has zero measure. The dual billiard map was introduced by Neumann in [Neu59] as a toy model for planet orbits.

We are mainly interested in the case of polygons. A particular class of polygons has been introduced by Kolodziej et al. in several articles, see [VS87, Kol89, GS92]. This class is named the quasi-rational polygons and contains all the regular polygons. They prove that every orbit of the outer billiard outside a polygon in this class is bounded. Recently Schwartz described a family of polygons for which there exist unbounded orbits, see [Sch07, Sch09]. In the case of the regular pentagon Tabachnikov completely

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described the dynamics of the outer billiard map in terms of symbolic dynamics, see [Tab95b].

In this paper we consider the outer billiard map outside regular polygons, and analyze the symbolic dynamics attached to this map. We are interested in the cases where the polygon has 3, 4, 5, 6 or 10 sides and give a complete description of the dynamics by a characterization of the language and the complexity function. We compute the global complexity of these maps, and generalize the result of Gutkin and Tabachnikov, see [GT06].

The description of a language associated to a dynamical system, is a way to understand the dynamics. Even if the dynamics is quite simple, the combinatorics of the language can be non trivial. Moreover the link between the combinatorics and the geometry is useful to see the properties of the dynamical system. For example in the case of inner billiard inside a square, the dynamics is easy since either the orbit is periodic or it is the orbit of a point under a rotation. But the computation of the complexity function via the bispecial words is not so simple, see [CHT02].

The study of the symbolic dynamics of these map outside a polygon is just at the beginning. By a result of Buzzi, see [Buz01], we know that the topological entropy is zero, thus the complexity grows as a sub-exponential. Recently Gutkin and Tabachnikov proved that the complexity function of polygonal outer billiard is always bounded by a polynomial, see [GT06].

2 Overview of the paper

In Section 3 we define the outer billiard map outside a polygon. In Section 4 we recall the basic definitions of word combinatorics and explain the partition associated to the dual billiard map. In Section 5 we simplify our problem, then in Section 6 we recall the different results on the subject, and in Section 7 we can state our results. The main case is the pentagonal case. We give the proof for this case, the other cases can be treated by a similar analysis. First in Section 8 we recall some facts on piecewise isometries. Then in Section 9 we use an induction method to describe the dynamics of the dual billiard map. Finally in Sections 10, 11 and 12 we describe the language of the dual billiard map outside the regular pentagon and finish the proof. Section 13 finishes the paper with a similar result for the regular decagon.

3 Outer billiard

We refer to [Tab95a] or [GS92]. We consider a convex polygon $P$ in $\mathbb{R}^2$ with $k$ vertices. Let $\mathcal{P} = \mathbb{R}^2 \setminus P$ be the complement of $P$. We fix an orientation of $\mathbb{R}^2$. 

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Definition 1. Denote by $\sigma_1$ the union of straight lines containing the sides of $P$. We consider the central symmetries $s_i, i = 0 \ldots k-1$ about the vertices of $P$. Define $\sigma_n$, where $n \geq 2$ is an integer, by $\sigma_n = \bigcup_{i=0}^{k-1} s_i \sigma_{n-1}$. Now the singular set is defined by:

$$Y = \bigcup_{n=1}^{\infty} \sigma_n.$$ 

For any point $M \in \overline{P} \setminus Y$, there are two half-lines $R, R'$ emanating from $M$ and tangent to $P$, see Figure 1. Assume that the oriented angle $R, R'$ has positive measure. Denote by $A^+, A^-$ the tangent points on $R$ respectively $R'$.

Definition 2. The outer billiard map is the map $T$ defined as follows:

$$T : \overline{P} \setminus Y \to \overline{P} \setminus Y$$

$$M \mapsto s_{A^+}(M)$$

where $s_{A^+}$ is the reflection about $A^+$.

Remark 1. This map is not defined on the entire space. The map $T^n$ can be defined on $\overline{P} \setminus \sigma_n$, but on this set $T^{n+1}$ is not everywhere defined. The definition set $\overline{P} \setminus Y$ is of full measure in $\overline{P}$.

Two important families of polygons have been defined in the study of this map: the rational polygons and the quasi-rational polygons.

Definition 3. A polygon $P$ is said to be rational if the vertices of $P$ are on a lattice of $\mathbb{R}^2$.

The definition of the quasi-rational polygons is more technical and we will not need it here. We just mention the fact that every regular polygon is a quasi-rational polygon.
4 Symbolic dynamics

4.1 Definitions

4.1.1 Words

For the notions of word, factor, substitution we refer to [PF02]. In the following, we will deal with several infinite words, thus we need a general definition of a language.

Definition 4. A language $L$ is a sequence $(L_n)_{n \in \mathbb{N}}$ where $L_n$ is a finite set of words of length $n$ such that for any word $v \in L_n$ there exists two letters $a, b$ such that $av$ and $vb$ are elements of $L_{n+1}$, and all factors of length $n$ of elements of $L_{n+1}$ are in $L_n$. $\text{Fact}(L)$ is the set of all factors of $L$.

Definition 5. The complexity function of a language $L$ is the function $p : \mathbb{N} \to \mathbb{N}$ defined by $p(n) = \text{card}(L_n)$.

4.1.2 Complexity

First we recall a result of the second author concerning combinatorics of words [Cas97].

Definition 6. Let $L = (L_n)_{n \in \mathbb{N}}$ be a language. For any $n \geq 0$ let $s(n) := p(n + 1) - p(n)$. For $v \in L_n$ let

$$
m_l(v) = \text{card}\{a \in A, av \in L_{n+1}\},
m_r(v) = \text{card}\{b \in A, vb \in L_{n+1}\},
m_b(v) = \text{card}\{(a, b) \in A^2, avb \in L_{n+2}\}.
$$

- A word $v$ is called right special if $m_r(v) \geq 2$.
- A word $v$ is called left special if $m_l(v) \geq 2$.
- A word $v$ is called bispecial if it is right and left special.
- $BL_n$ denotes the set of bispecial words of length $n$.

$b(n)$ denotes the sum $b(n) = \sum_{v \in BL_n} i(v)$, where $i(v) = m_b(v) - m_r(v) - m_l(v) + 1$.

Lemma 1. Let $L$ be a language. Then the complexity of $L$ satisfies for every integer $n \geq 0$:

$$s(n + 1) - s(n) = b(n).$$

For the proof of the lemma we refer to [Cas97] or [CHT02].

Definition 7. A word $v$ such that $i(v) < 0$ is called a weak bispecial. A word $v$ such that $i(v) > 0$ is called a strong bispecial. A bispecial word $v$ such that $i(v) = 0$ is called a neutral bispecial.
4.2 Coding

We introduce a coding for the dual billiard map. Recall that the polygon $P$ has $k$ vertices.

**Definition 8.** The sides of $P$ can be extended in half-lines in the following way: denote these half lines by $(d_i)_{0 \leq i \leq k-1}$ we assume that the angle $(d_i, d_{i+1})$ is positive. They form a cellular decomposition of $\overline{P}$ into $k$ closed cones $V_0, \ldots, V_{k-1}$. By convention we assume that the half line $d_i$ is between $V_{i-1}$ and $V_i$ see Figure 2.

![Figure 2: Partition](image)

Now we define the coding map, we refer to Definition 1:

**Definition 9.** Let $\rho$ be the map

$$\rho : \overline{P} \setminus Y \rightarrow \{0, \ldots, k-1\}^\mathbb{N}$$

where $u_n = i$ if and only if $T^n M \in V_i$.

Now consider the factors of length $n$ of $u$, and denote this set by $L_n(M)$. Remark that $T^n M \in V_i \cap V_{i+1}$ is impossible if $M \notin Y$.

**Definition 10.** We introduce the following set

$$L_n = \bigcup_{M \in \overline{P} \setminus Y} L_n(M).$$

This set corresponds to all the words of length $n$ which code outer billiard orbits. Then the set $L = \bigcup_n L_n$ is a language. It is the language of the outer billiard map. We denote the complexity of $L$ by $p(n)$, see Definition 5.

$$p(n) = \text{card}(L_n).$$

**Definition 11.** The set $\{0, \ldots, k-1\}^\mathbb{N}$ has the natural product topology. Then $X$ denotes the closed set $X = \rho(\overline{P} \setminus Y)$.
5 Simplification of the problem

In this part we introduce a new map $\hat{T}$ to simplify the problem. This map is not the first return map on $V_0$. We use it instead of the first return map, because it seems that this map can be used for all the regular polygons.

5.1 First remarks

**Lemma 2.** Let $P$ be a convex polygon, and $h$ an affine map of $\mathbb{R}^2$ preserving the orientation, then the languages of the outer billiard maps outside $P$ and $h(P)$ are the same.

**Proof.** The proof is left to the reader. \hfill \Box

Remark that an affine map preserves the set of lattices. Thus if $P$ is rational, then $h(P)$ is rational for each affine map $h$. Also, the outer billiard map outside any triangle has the same language, so it is sufficient to study the equilateral triangle, see Lemma 2.

5.2 A new coding for the regular polygon

Let $P$ be a regular polygon with $k$ vertices, and $R$ be the rotation of angle $-2\pi/k$, centered at the center of the polygon. Consider one sector $V_0$ and define the map:

$$
\bigcup_i V_i \rightarrow \mathbb{N} \\
y \mapsto n_y
$$

where the integer $n_y$ is the smallest integer which maps the sector $V_i$ containing $y$ to $V_0$ by a power of the rotation $R$. Then we define a new map

**Definition 12.** The map $\hat{T}$ is defined in $V_0$ by the formula

$$
\hat{T}(x) = R^{n_Tx}Tx.
$$

**Lemma 3.** The integer $n_Tx$ takes the values $1$ to $j = \lfloor \frac{k+1}{2} \rfloor$. The map $\hat{T}$ is a piecewise isometry on $j$ pieces.

**Proof.** We will treat the case where $k$ is even, the other case is similar. Assume $k = 2k'$, then we can assume that the regular polygon has as vertices the complex numbers $e^{i\pi n/k'}, n = 0 \ldots k - 1$ and that $V_0$ has 1 as vertex. Consider the cone $V = TV_0$ of vertex 1 obtained by a central symmetry from the cone $V_0$. We must count the number of intersection points of this cone with the cones $V_i, i = 0 \ldots k - 1$. The polygon is invariant by a central symmetry, this symmetry maps the cone $V_i$ to the cone $V_{k' + i}$. We deduce that if the cone $V_i$ intersects $V$, then the cone $V_{k' - i}$ cannot intersect it. Moreover it is clear that each cone $V_i, 1 \leq i \leq k'$ intersects $V$, thus $n_Tx$ takes the values $1$ to $k'$. Now for each value of $n_Tx$ we obtain an isometry, thus we obtain a piecewise map defined on $j = k'$ sets. \hfill \Box
Definition 13. Let $\eta$ be the map defined as

$$\eta : V_0 \setminus Y \to \{1, \ldots, j\}^N$$

$$x \mapsto (n_{T(\hat{T}^i x)})_{i \in N}$$

As in Definition 10, let $L'$ be the language of $\hat{T}$ related to the coding $\eta$.

Lemma 4. We have

$$\hat{T}^k(x) = R^{n-k} T^k x.$$  

Proof. This lemma is a consequence of the following fact: If $A, B$ are two consecutive vertices of the polygon for the orientation, denote by $s_A, s_B$ the central symmetries about them, then we have $R s_B = s_A R$. This relation implies that $R$ and $T$ commute:

$$RT = TR.$$  

Lemma 5. If $x \in V_0 \setminus Y$, then the codings $(u_n) = \rho(x)$ and $(v_n) = \eta(x)$ are linked by

$$v_n = u_{n+1} - u_n \mod k.$$  

Proof. Consider two consecutive elements of the sequence $u$ with values $a, b$. It means $T^n x \in V_a, T^{n+1} x \in V_b$. Now the rotation $R^{b-a}$ maps $V_b$ to $V_a$, thus we deduce that $R^{b-a} T[T^n x]$ belongs to $V_a$, this implies with the help of preceding Lemma that $v_n = b - a \mod k.$

The preceding Lemma implies that the study of the map $\hat{T}$ will give information for $T$.

Lemma 6. With the notations of Definitions 10, 13 we have

$$p_L(n) = k p_{L'}(n - 1).$$

Moreover the map $u \mapsto v$ defined by $v_i = u_{i+1} - u_i$, for $0 \leq i \leq n - 2$ if $u = u_0 u_1 \ldots u_{n-1}$ is a $k$-to-one map.
Proof. The regular polygon is invariant by the rotation $R$, thus the points $x$ and $R^i x, 0 \leq i \leq k-1$ have the same coding in $L'$. Thus the map is not injective and the pre-image of a word consists of $k$ words. By definition it is surjective. Now the formula for the complexity function is an obvious consequence of the formula $v_n = u_{n+1} - u_n$, see Lemma 5.

6 Background

Few results are known about the complexity of the outer billiard map. Gutkin and Tabachnikov proved in [GT06] the following result.

Theorem 1. Let $P$ be a convex polygon

- If $P$ is a regular polygon with $k$ vertices then there exist $a, b > 0$ such that
  \[ an \leq p(n) \leq bn^{r+2}. \]
  The integer $r$ is the rank of the abelian group generated by translations in the sides of $P$. We have $r = \phi(k)$, where $\phi$ is the Euler function.

- If $P$ is a rational polygon, then there exist $a, b > 0$ such that
  \[ an^2 \leq p(n) \leq bn^2. \]

In fact their theorem concerns the more general family of quasi-rational polygons that includes the regular ones, but we will not prove a result about this family of polygons. Remark that for the regular pentagon, we have $r = 4$.

7 Results

We obtain two types of results: The description of the language of the dynamics, and the computation of the complexity. The results are obtained for two types of polygons: the triangle, the square and the regular hexagon which are rational polygons; and the regular pentagon which is a quasi-rational polygon.

7.1 Languages

We characterize the languages of the outer billiard map outside regular polygons: We will use Lemma 6 and work with the language $L'$. Moreover we will give only infinite words. The language is the set of finite words which appear in the infinite words.
Definition 14. Consider the three following endomorphisms of the free group $F_3$ defined on the alphabet $\{1; 2; 3\}$

\[
\begin{align*}
\sigma : & \quad 1 \rightarrow 1121211 \\
& \quad 2 \rightarrow 111 \\
& \quad 3 \rightarrow 3
\end{align*}
\]

\[
\begin{align*}
\psi : & \quad 1 \rightarrow 2232232 \\
& \quad 2 \rightarrow 232 \\
& \quad 3 \rightarrow 2^{-1}
\end{align*}
\]

\[
\begin{align*}
\xi : & \quad 2 \rightarrow 2 \\
& \quad 3 \rightarrow 3
\end{align*}
\]

Theorem 2. Let $P$ be a triangle, a square, a regular hexagon or a regular pentagon. Then the language $L'$ of the dynamics of $\hat{T}$ is the set of factors of the periodic words of the form $z^\omega$ for $z \in Z$, where

- If $P$ is a triangle

\[
Z = \bigcup_{n \in \mathbb{N}} \{1(21)^n, 1(21)^n 1(21)^{n+1}\}.
\]

- If $P$ is the square

\[
Z = \bigcup_{n \in \mathbb{N}} \{12^n\}.
\]

- If $P$ is the regular hexagon

\[
Z = \bigcup_{n \in \mathbb{N}} \{23^n, 23^n 23^{n+1}\} \cup \{1\}.
\]

- If $P$ is the regular pentagon then $Z$ is the union of

\[
\begin{align*}
& \bigcup_{n \in \mathbb{N}} \{\sigma^n(1), \sigma^n(12)\}, \\
& \bigcup_{n,m \in \mathbb{N}} \{\psi^m(2), \psi^m(2223), \psi^m \circ \sigma^n(1), \psi^m \circ \sigma^n(12)\}, \\
& \bigcup_{n,m \in \mathbb{N}} \{\psi^m \circ \xi \circ \sigma^n(1), \psi^m \circ \xi \circ \sigma^n(12)\}.
\end{align*}
\]

7.2 Complexity

In the statement of Theorem 3 we give the formula for $p_{L'}$. Lemma 6 can be used to obtain the formula for the complexity of the language $L$.

Theorem 3. For a triangle, we have

\[
p_{L'}(n) = \frac{5n^2 + 14n + f(r)}{24},
\]

where $r = n \mod 12$ and $f(r)$ is given by

<table>
<thead>
<tr>
<th>$r$</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f(r)$</td>
<td>24</td>
<td>29</td>
<td>24</td>
<td>9</td>
<td>8</td>
<td>21</td>
<td>24</td>
<td>17</td>
<td>0</td>
<td>-3</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>
• For a square we obtain:

\[ p_{L'}(n) = \frac{1}{2} \left\lfloor \frac{(n+2)^2}{2} \right\rfloor. \]

• For a regular hexagon:

\[ p_{L'}(n) = \left\lfloor \frac{5n^2 + 16n + 15}{12} \right\rfloor. \]

• For a regular pentagon, let \( \beta \) be the real number:

\[
\beta = \frac{14}{15} + \sum_{n \geq 0} \left( \frac{7}{48.6^{n}.2 + 14 + 2(-1)^n} + \frac{7}{18.6^{n}.2 + 14 - (-1)^n} \right) - \sum_{n \geq 0} \left( \frac{7}{78.6^{n}.2 + 14 + 5(-1)^n} + \frac{7}{48.6^{n}.2 + 14 - 5(-1)^n} \right).
\]

then we have

\[ p_{L'}(n) \sim \frac{\beta n^2}{2}, \]

with \( \beta \sim 1.060. \)

• For a regular decagon, there exists a constant \( C > 0 \) such that

\[ p_{L'}(n) \sim Cn^2. \]

### 7.3 Remarks

The proof uses the same method in all the cases. Thus we only treat the case of pentagon and decagon which are harder. The other cases are similar, the dynamics is quite elementary since all the orbits are periodic. The computation of the complexity function uses the same method as in the pentagonal case.

The differences between the cases \( n = 3, 4, 6 \) and \( n = 5, 10 \) come from the following facts. The first cases are much easier to study, for a dynamical point of view, because the respective polygons are on a lattice. This is not true anymore for \( n = 5, 10 \). In Figure 4 and 5 we show the different tilings of the plane obtained by the sequence \((T^{-n}d)_{n \in \mathbb{N}}\) where \( d \) is a line supporting an edge of the regular polygon. In the first cases, we obtain a regular tiling of the plane by regular polygons. In the case of a regular pentagon we see that the adherence of this orbit has a fractal structure. Remark that the case of the regular octogon has recently been studied by Schwartz, see [Sch10]. But the point of view is different, the paper focuses on the arithmetic graph and not on the symbolic dynamics.
8 Piecewise isometry of Tabachnikov

In this section we recall some results proved by Tabachnikov in [Tab95b].

8.1 Definition and results

Consider Figure 6. We define a piecewise isometry \((Z, G)\) on the union of two triangles

\[ Z = AFC \cup HFE. \]

The two triangles are isosceles, the angle in \(A\) equals \(2\pi/3\), \(AF = 1\), and \(AC = 1 + \sqrt{3}/2\). The map \(G : Z \mapsto Z\) is defined as follows:

- a rotation of center \(O_1\) and angle \(-3\pi/5\) which sends \(C\) to \(E\), on \(AFC\).
• a rotation of center $O_2$ and angle $-\pi/5$ which sends $H$ to $C$ on $HFE$.

![Figure 6: Piecewise isometry $G$](image)

**Definition 15.** Let $\sigma$ be the substitution:

$$\sigma : \begin{cases} 1 \rightarrow 1121211 \\ 2 \rightarrow 111 \end{cases}$$

and let $u$ be its fixed point.

**Definition 16.** We denote by $V_{\text{per}}$ the set of periodic points for $G$, and by $V_\infty$ the set $Z \setminus V_{\text{per}}$.

**Theorem 4.** [Tab95b] We have:

1. If $x$ is a point with non periodic orbit under $G$, then the dynamical system $(O(x), G)$ is conjugated to $(O(u), S)$ where $S$ is the shift map, and $O(x)$ denotes the closure of the orbit of $x$.

2. A connected component of $V_{\text{per}}$ is a regular pentagon or a regular decagon.

3. Each point in a regular decagon has for coding an infinite word included in the shift orbit of $(\sigma^n(1))^\omega$, $n \in \mathbb{N}$. The points inside regular pentagons correspond to the words $(\sigma^n(12))^{\omega}$, $n \in \mathbb{N}$.

**Corollary 1.** The aperiodic points have codings included in the orbit $O(u)$.

### 8.2 Link between $(Z, G)$ and the outer billiard outside the regular pentagon

We will make more precise the statement of Lemma 3. We use the same definitions, but the sector will be denoted by $V$.

**Definition 17.** The points refer to Figure 7. We define three sets

- $U_1$ is the triangle $AEB$. 

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• $U_2$ is an infinite polygon with vertices $IBE$.

• $U_3$ is a cone of vertex $I$.

A straightforward analysis of Figure 7 allows us to prove the following lemma.

**Lemma 7.** The map $\hat{T}$, see definition 12, is defined on three subsets $U_1, U_2, U_3$.

$$V = U_1 \cup U_2 \cup U_3.$$  

The images of $U_1, U_2, U_3$ by $\hat{T}$ verify the following properties:

• The first cell $U_1$ has for image the triangle $ACF$ and $\hat{T}|_{U_1} = RT$.

• On the second cell $U_2$, we have $\hat{T}|_{U_2} = R^2T$, and the image of $U_2$ is an infinite polygon with vertices $CFG$.

• On the third set, we have $\hat{T}|_{U_3} = R^3T$, and the image of $U_3$ is a cone of vertex $G$.

• The union of the triangles $ACF$ and $HFE$ is invariant by $\hat{T}$:

$$U_1 \cup (\hat{T}U_1 \cap U_2).$$  

• The restriction of the map $\hat{T}$ to this invariant set is the map $(Z, G^{-1})$.

• The set $[U_2 \setminus (\hat{T}U_1 \cap U_2)] \cup U_3$ is also invariant.


9 Dynamics on $U_2 \cup U_3$

The last point of the preceding lemma implies that we can restrict our study
to a piece of $U_2 \cup U_3$. By calculation with complex numbers we prove:

Lemma 8. The dynamics on the invariant set $[U_2 \setminus (\hat{T}U_1 \cap U_2)] \cup U_3$ is given by:

- The map restricted to $U_3$ is a rotation by angle $-\pi/5$.
- The map restricted to $U_2 \setminus Z$ is a rotation by angle $\pi/5$.

We use the coding related to $\hat{T}$, see Subsection 5.2. Using Lemma 7 we see that on the invariant set $Z$ we have the same coding as in the piecewise isometry of Tabachnikov.

Definition 18. We define the map

$$F : \{1; 2; 3\}^* \to Isom(\mathbb{R}^2)$$

$$v \mapsto F(v)$$

where $v = v_0 \ldots v_{n-1}$ is a finite word over the alphabet $\{1, 2, 3\}$, $F(v)$ is the composition of isometries: $F(v) = F(v_{n-1}) \circ \ldots \circ F(v_0)$. The map $F(i)$ coincides with $\hat{T}$ on $U_i$ for $i = 1 \ldots 3$.

Remark that $F(2)$ and $F(3)$ are rotations of opposite angles. $F(2)$ has angle $\pi/5$ and $F(1)$ has angle equal to $3\pi/5$.

Now some computations on isometries allow us to prove the following fact:

Lemma 9. There exists a translation $t$ and a rotation $u$ such that

- For any word $v$ of the language of $\hat{T}$ we have:
  $$F(\psi(v)) \circ t = t \circ F(v), F(\xi(v)) \circ u = u \circ F(v).$$

- For the language of the map $\hat{T}$, we have equivalence between
  - $v$ is the code of a periodic point.
  - $\psi(v)$ is the code of a periodic point.

- For the language of the map $\hat{T}$, we have equivalence between
  - $v$ is a periodic word.
  - $\xi(v)$ is a periodic word.
10 Proof of Theorem 2 for the regular pentagon

Before the proof we explain the statement of the theorem from a geometric point of view.

We can split the language in different sets of periodic words with following periods:

- The words given by iteration of $\sigma$ on 1 or 12.
- The words obtained by the iterations of 2223 or 2 under $\psi$.
- The iterates of $\psi$ on the periodic words of the first class. They corresponds to coding of orbits of the following points: Take one point in $Z$, translate it by some power of $t$.
- The words obtained by composition of $\xi$ and a power of $\psi$ on the first words.

We use Corollary 9. We construct three invariant regions which will glue together and form a fundamental domain for the action of the translation $t$. The three sets are given by

- The properties of the substitution $\psi$ imply the existence of a translation $t$ which is parallel to a side of the cone. Let $j$ be an integer, then the set $Z + jt$ is not invariant by $\hat{T}$. Now consider its orbit:

$$\bigcup_{i \in \mathbb{N}} \hat{T}^i(Z + jt).$$

First by Lemma 8 we know that its orbit is inside $U_2 \cup U_3$. $Z$ is made of one big triangle and one small triangle. We claim that the five first iterations form an invariant set made of eight big triangles and three small ones. The symbolic dynamics inside this set is given by the composition of $\psi^j$ and $\sigma$. It is the first invariant ring.

- Now we look at the second substitution $\xi$. Corollary 9 shows that there exists an invariant ring corresponding to the cells of the orbit under the shift of $(32222)^o$. The symbolic dynamics inside this set is given by the composition of $\xi$ and one iterate of $\sigma$.

- Moreover by Lemma 8 there is an invariant polygon inside $U_2$, which is a regular decagon.

These three invariant rings glue together by trigonometric arguments.

Now we have a compact set inside $V$ with a symbolic description. These words are thus obtained as the $\mathbb{Z}^2$ sequences:

$$\psi^j \circ \sigma^i(1), \psi^j \circ \xi \circ \sigma^i(1), \psi^j(2223).$$
Now consider the parallelogram in \( V \) with sides parallel to the axis of \( V \) and of lengths \( |t| \) and the golden mean. Then consider the images of it by all the power of \( t \). It forms a strip. Let \( m \) be a point in \( V \), then either it is in the strip or there exists an integer \( n_0 \) such that \( T^{n_0}m \) is inside this strip. Indeed outside the strip \( T \) acts as a rotation. Thus the dynamics of every point can be described with the preceding description.

11 Bispecial words

In this Section we will describe the bispecial words of the language of the outer billiard map outside the regular pentagon.

**Definition 19.** We introduce different maps and words to simplify the statement of the result.

\[
\begin{align*}
\Phi &\begin{cases}
1 \mapsto 1 \\
2 \mapsto 2 \\
3 \mapsto 23
\end{cases} & \text{• } \psi_{\{2,3\}} = \tilde{x}. \\
\tilde{\psi} &\begin{cases}
1 \mapsto 23232 \\
2 \mapsto 32 \\
3 \mapsto 3
\end{cases} & \text{• } \hat{\beta}(w) = \frac{23232\beta(w)}{\beta(w)} \text{ for all word } w. \\
\hat{\chi} &\begin{cases}
1 \mapsto 3222 \\
2 \mapsto 2
\end{cases} & \text{• } x_n = \hat{\sigma}(1) \text{ for all integer } n. \\
\hat{\xi} &\begin{cases}
1 \mapsto 3222 \\
2 \mapsto 2
\end{cases} & \text{• } y_n = \hat{\sigma}(1111) \text{ for all integer } n. \\
\psi_{\{1,2\}} = \tilde{\beta}. \\
\end{align*}
\]

Remark that we have \( \psi = \Phi \circ \tilde{\psi} \circ \Phi^{-1}, \xi = \Phi \circ \tilde{\xi} \circ \Phi^{-1} \).

The aim of this part is to prove

**Proposition 1.** The bispecial words of the language \( L' \) of the outer billiard outside the regular pentagon form 24 families, according to preceding definition.

- **The empty word** \( \varepsilon \), with \( i(\varepsilon) = 2 \).
- **The word** \( 2 \), with \( i(2) = 0 \).
- **The weak bispecial words** are with \( k, n \in \mathbb{N} \):
  \[
  \begin{align*}
  \Phi(\hat{x}_k(2222)) &\quad \Phi(\hat{x}_k(22322)) &\quad \Phi(\hat{x}_k(232232)) &\quad \Phi(\hat{x}_k(2323232)), \\
  \Phi(\hat{x}_k \circ \tilde{\xi}(z_n)) &\quad \Phi(\hat{x}_k \circ \tilde{\xi}(t_n)) &\quad \Phi(\hat{x}_k \circ \tilde{\beta}(z_n)) &\quad \Phi(\hat{x}_k \circ \tilde{\beta}((t_n)), \\
  &\quad z_n, t_n
  \end{align*}
  \]

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11.1 Notations
We use Figure 8 and define five languages $L_0, L_1, L_2, L_4, L_3$.

**Definition 20.** We denote $L_0, L_1, L_2, L_4, L_3$ the languages made respectively by factors of the following words:

- $L_0 = \bigcup_{n \geq 0} \sigma^n(1)\omega \cup \sigma^n(12)\omega$.
- $L_1 = \tilde{\xi}(L_0)$.
- $L_2 = \tilde{\beta}(L_0)$.
- $L_3 = \bigcup_{m \geq 1} \tilde{\chi}^m(L_3) \cup \tilde{\chi}^m(L_2) \cup \tilde{\chi}^m(L_1)$.
- $L_4 = 2\omega \cup (223)\omega$.
11.2 Step one

11.2.1 Simplification of the problem

Lemma 10. The language $L'$ of the outer billiard map outside a regular pentagon is the union:

$$L' = \text{Fact}(\Phi(L_0 \cup L_1 \cup L_2 \cup L_4 \cup L_3)).$$

Proof. By using the conjugation by $\Phi$ and Theorem 2 we obtain a description of our language. The map $\Phi^{-1}$ is given by $\begin{cases} 1 \mapsto 1 \\ 2 \mapsto 2 \\ 3 \mapsto 2^{-1}3 \end{cases}$. Thus we deduce that $\Phi^{-1}(L_0) = L_0$, and deduce the result. \hfill \square

Definition 21. By preceding Lemma $L'$ is the union of $L_0$ and the image by $\Phi$ of a set. We denote $L_\Phi = L_1 \cup L_2 \cup L_4 \cup L_3$ so that $L' = \Phi(L_\Phi) \cup L_0$.

The preceding operations can be summarized in Figure 8.

11.2.2 Study of the map $\Phi$

In this part we explain how to manage the map $\Phi$ and restrict the study to the language $L_\Phi$. In order to prove this result we use a synchronization lemma

Lemma 11. If $w$ is a factor of the language $\Phi(L_\Phi)$, then there exists a unique triple $(s,v,p)$ such that $w = svp$ with $s \in \{\varepsilon, 3\}, v \in L_\Phi, p \in \{\varepsilon, 2\}$, with the additional condition $v \in A^*2 \Rightarrow p = 2$.

Proof. First we are only interested in the case where $w = s\Phi(v)$. If $w$ begins by 1, then it is clear that $w$ can be written in the form $\Phi(1v)$. If $w$ begins by 2 then three possibilities appear for the beginning: 21 thus we write $w = \Phi(21v)$; or 22 and $w$ can be written as $\Phi(2v)$; and last possibility 23, then $w = \Phi(3v)$. If $w$ begins by 3, we do the same thing and remark that the only problem is if $w$ begins with 32. In this case we have $s = 3$. The first part of the lemma is proven. Now we consider words of the form $w = \Phi(v)p$.

The proof is similar: the uniqueness is a consequence of the proof. \hfill \square

Corollary 2. A word $w$ is bispecial in the language $L'$ if and only if either

- 1 occurs in $w$ and $w$ is bispecial in $L_0$, with same index.
- 3 or 22 occurs un $w$, and $w = \hat{\Phi}(v)$ with $v$ bispecial in $L_\Phi$.
- $w = \varepsilon$.
- $w = 2$. 

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Proof. We apply preceding Lemma to $w$. Now if $w$ is a bispecial word of $\Phi(L)$, then $s = \varepsilon$, indeed the properties of $\Phi$ imply $13, 33$ do not belong to $\Phi(L)$. Since the image of each letter by $\Phi$ ends with the same letter we remark that $xw \in \Phi(L) \Rightarrow xv \in L$. There are two cases

- $p = \varepsilon$: then the extensions of $w$ must belong to $\Phi(L)$. It implies $v1 \in L$ and either $v2$ or $v3$ belong to $L$ (or both).
- If $p = 2$, then $w1$ or $w2$ or $w3$ belong to $\Phi(L)$. It implies $v21 \in L$ or $v22 \in L$ resp. $v23 \in L$ resp. $v3 \in L$.

Then we can summarize this study in the four cases

- $w1, w2 \in \Phi(L)$, then $v21$ and $v22$ or $v23 \in L$. So $v2$ is bispecial in $L$.
- $w1, w3 \in \Phi(L)$, then $v2, v3 \in L$, so $v$ is bispecial in $L$.
- $w2, w3 \in \Phi(L)$, then $v2, v3 \in L$, so $v$ is bispecial in $L$.
- $w1, w2, w3 \in \Phi(L)$, then both $v$ and $v2$ are bispecial in $L$.

This finishes the proof. \qed

Remark 2. This lemma allows us to forget the map $\Phi$ until Section 12 and to study the bispecial words of the language $L$.

11.3 Abstract of the method

The method to list the bispecial words is the following. We begin by the bispecial words which are not in the intersection of two of the languages $L_1, L_2, L_3$. For the language $L_4$ we prove that these words are images of bispecial words of $L_2 \cup L_1$. Then we prove that bispecial words in $L_1 \cup L_2$ are images of bispecial words in $L_0$, finally we list the bispecial words of $L_0$. Then it remains to treat the words which are in the intersection of two languages.

11.4 Different languages

We will need the following result.

Lemma 12. We have

$$L_0 \subset \{1, 12\}^*, L_1 \subset \{3222, 32222\}^*, L_2 \subset \{23, 223\}^*, L_4 \subset \{3, 32\}^*, L_3 \subset \{2, 223\}^*$$

Proof. The proof just consists in the remark that $22$ does not appear in $L_0$. Thus in $L_2$, the word $32$ appears if $u$ contains $1$ and $322$ appears when $u$ contains $21$. For $L_1$, the word $3222$ appears in $\xi(1)$, and the word $32222$ appears from the word $12$. From the image by $\tilde{\chi}$ of $32, 3222$ and $32222$ we deduce the result. \qed
11.4.1 Language \(L_4\)

**Proposition 2.** If \(w\) is a non empty bispecial word of \(L_4\), then we have \(w = s\hat{\chi}(v)p\) with \(s = \varepsilon, p = 3\), where \(v \in L_\Phi\) is a bispecial word of \(L_\Phi\) with the same extensions as \(w\).

*Proof.* By the definition of \(L_4\) we have \(w \in F(\chi(L_1 \cup \ldots L_3))\). By Lemma 12 a bispecial word must begin and end with the letter 3. Now since \(L_4\) is built from the words 3 and 32 we can remark that these words are images of 3 and 2 by \(\hat{\chi}\). The last letter of \(w\) can not be the image by \(\hat{\chi}\) of 3 since it must be prolonged by 2.

**Corollary 3.** If \(w\) is a bispecial word of \(L_4\) then there exists an integer \(k\) such that \(w = \hat{\psi}^k(v)\), with \(v \in L_1 \cup L_2 \cup L_3\). Moreover \(v\) is a bispecial word in \(L_\Phi\) with the same multiplicity.

*Proof.* By the preceding result \(w = \hat{\psi}(v)\) and \(v\) is a bispecial word. Thus if \(v\) is not empty, we deduce \(w = \hat{\psi}^2(v')\). We do the same thing until \(v'\) belongs to \(L_1 \cup L_2 \cup L_3\). This must happen since the lengths decrease.

11.4.2 Language \(L_3\)

**Lemma 13.** The bispecial words in this language are:

\[\{\varepsilon, 2, 22\}\]

*Proof.* The proof is left to the reader.

11.4.3 Language \(L_1\)

**Lemma 14.** A bispecial word \(w\) of \(L_1\) fulfills one of the following facts.

- \(w \in \{\varepsilon, 2, 22, 222, 2222, 22322\}\).
- \(w = \hat{\xi}(v)\) where \(v\) is bispecial in \(L_0\), \(v \neq \varepsilon\).

*Proof.* First it is clear that a bispecial word in \(L_1\) must begin and end with 2. If \(w\) is not a factor of 232232, then assume \(w\) does not contains 222 as a factor. By Lemma 12, \(L_1 \subset \{2, 322\}^*\) we deduce that \(w\) is a factor of \((223)^\omega\). Thus we have \(w = (223)^k22\), and we deduce \(k = 1\) since \(w \notin F(232232)\).

There remains one case corresponding to 222 \(\in F(w)\). Then by definition of \(L_1\) we have \(w \in \hat{\xi}(L_0)\). By Lemma 12 the number of consecutive 2 is equal to 3 or 4, moreover the letter 3 is isolated. Then if \(w\) is a bispecial word we deduce that \(w\) begins with 2. Now 2\(w\) must be a word of the language. We deduce that \(w\) begins with three letters 2. Now we remark that 3222 is equal to \(\hat{\xi}(1)\). This implies that the suffixe of \(w\) which prolong 222 is the image of one word by \(\hat{\xi}\). To finish the proof it remains to list the bispecial words factors of 232232.
11.4.4 Language $L_2$

Lemma 15. A bispecial word $w$ of $L_2$ fulfills one of the following facts.

- $w \in F(23232)$.
- $w = \hat{\beta}(v)$ where $v$ is bispecial in $L_0$, $v \neq \varepsilon$.

Proof. First it is clear that a bispecial word in $L_1$ must begin and end by 2. By Lemma 12, we obtain $L_2 \subset \{23232, 2323232\}^*$. We split the proof in two cases: $23232 \in F(w)$ or $23232 \notin F(w)$. For the first case since $w$ is a bispecial word we have $2w \in L_2$. Then Lemma 12 shows that 22 can only be extended by 3232, thus $w$ begins with 23232, and $w = \hat{\beta}(v)$.

11.4.5 Language $L_0$

Lemma 16. The language $L_0$ fulfills the following three properties:

- $11211 \notin L_0$.
- $22 \notin L_0$.
- Three consecutive occurrences of 2 are of the forms: $21^l 212$ or $2121^l 2$ with $l \in \{1, 4, 7\}$.

The following words are bispecial words of $L_0$:

- $1^i$ for $i = 0, 2, 3, 5, 6$ and it is an ordinary bispecial word: $i(1^i) = 0$. Thus they do not modify the complexity.
- $1^i$ for $i = 1, 4$ and it is a strong bispecial word: $i(1) = i(1^4) = 1$.
- $12121, 1^7$ are weak bispecial words: $i(12121) = i(1^7) = -1$.

The proof is left to the reader.

Lemma 17. We have different cases for a non-ordinary bispecial word $w$ of $L_0$.

- $w = 1^n, n \in \{1, 4, 7\}$.
- $w = 12121$.
- $w = \hat{\sigma}(v)$ where $v$ is a non-ordinary bispecial word of $L_0$ and $i(w) = i(v)$.

Proof. First we consider the words without 2, then the word is a power of 1, and preceding Lemma shows the different possibilities. Now if the word contains only one letter 2, then the word has the form $w = 1^n 21^n$, now the fact that $11211 \notin L_0$ (see preceding Lemma) shows that the only possibility
is 121 which is ordinary. The case where $w$ contains at least two letters 2 remains. Then either $w$ contains 212 or the word is a factor of $\sigma(L_0)$. We have different subcases for a bispecial word $w = 1^m2\ldots21^n$ of $L_0$ factor of $u$ due to the preceding Lemma.

- $m = 1$, then the word $1w = 112\ldots21^n$ must belong to the language. This implies that $w = 1212\ldots21^n$, but the fact that $2w$ exists implies now that $w = 12121$.

- $m \in \{4, 7\}$, then $m = 7$ is clearly impossible. One case remains which can be written by symmetry as $w = 11112\ldots21111$. An easy argument of synchronization finishes the proof.

The preceding lemma implies that the bispecial words of $L_0$ are of the form

**Corollary 4.** For the long bispecial words there are four families of words.

- $x_n = \hat{\sigma}^n(1), n \in \mathbb{N}$, $i(\hat{\sigma}^n(1)) = 1$.
- $y_n = \hat{\sigma}^n(1^4), n \in \mathbb{N}$, $i(\hat{\sigma}^n(1^4)) = 1$.
- $z_n = \hat{\sigma}^n(12121), n \in \mathbb{N}$, $i(\hat{\sigma}^n(12121)) = -1$.
- $t_n = \hat{\sigma}^n(1^7), n \in \mathbb{N}$, $i(\hat{\sigma}^n(1^7)) = -1$.

The two first families are made of strong bispecial words, the two last are weak bispecial words.

### 11.5 Intersection of languages

We interest in the words which belong to different languages.

In the following Lemma we denote by $L_{ijk}$ the language intersection of the languages $L_i, L_j$ and $L_k$ for $i, j \in \{1\ldots4\}$.

**Lemma 18.** The words which belong to at least two languages are:

- $22 \in L_{124}, 23 \in L_{1234}, 32 \in L_{1234}$.
- $222 \in L_{14}, 223 \in L_{124}, 232 \in L_{1234}, 322 \in L_{124}, 323 \in L_{23}$.
- $2222 \in L_{14}, 2232 \in L_{124}, 2322 \in L_{124}, 2323 \in L_{23}, 3223 \in L_{24}, 3232 \in L_{23}$.
- $22322 \in L_{14}, 23223 \in L_{24}, 23232 \in L_{23}, 32232 \in L_{24}, 32323 \in L_{23}$.
- $232232 \in L_{24}, 232323 \in L_{23}, 322323 \in L_{23}$.
- $2323232 \in L_{23}, 3232323$.

**Proof.** We consider the words by family of different lengths. When we have listed all the words of a given length $i$, we consider the words of length $i+1$ which contain one of the preceding words as prefix or suffix. Then we use Lemma 12 to verify if this word is in two languages. This allows us to obtain the first list, after this it remains to look at the bispecial words.

**Corollary 5.** We have

\[
L_1 \cap L_0 = \{\varepsilon, 2\}.
\]

\[
L_1 \cap L_4 = F(232).
\]

\[
L_1 \cap L_3 = F(22322) \cup \{22, 222\}
\]

\[
L_4 \cap L_3 = F(232).
\]

\[
L_2 \cap L_3 = F(23232).
\]

\[
L_2 \cap L_4 = F(2323232)
\]

**Proof.** The proof is left to the reader.

**Corollary 6.** The bispecial words of $L_\Phi$ belonging to at least two of the languages $L_1, L_2, L_3, L_4$ are

- The ten strong bispecial words,

  \[
  \varepsilon, 2, 3, 22, 33, 222, 323, 23232, 32323.
  \]

- The four weak bispecial words:

  \[
  2222, 22322, 232232, 2323232.
  \]

### 11.6 Proof of Proposition 1

First, Lemma 11 implies that a bispecial word $w \in L'$ can be written as $w = \Phi(v)$ where $v \in L_\Phi$ is a bispecial word. Now we are interested in a bispecial word $v$ in $L_\Phi$. Several cases appear

- If $v \in L_0$, then Corollary 4 shows that $v$ is inside four families of words.

- If $v \in L_1$ then Lemma 14 implies that $v = \xi(v')$ with $v' \in L_0$ or $v$ is element of a finite family. Thus the preceding point completes the list of bispecial words of $L_1$.

- If $v \in L_2$, then Lemma 15 implies that except for a finite list of words, we can write $v = \beta(v')$ with $v' \in L_0$.  

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• If \( v \in L_3 \) then Lemma 13 gives the complete list of bispecial words.

• If \( v \in L_4 \), then by Corollary 3 we know that \( v = \hat{\psi}^k(v') \) where \( v' \in L_1 \cup L_2 \cup L_3 \).

• Corollary 6 and the preceding points allow us to finish the proof.

12 Proof of Theorem 3

We use Proposition 1 to compute the different lengths of these bispecial words. The proof is a calculation using linear algebra, thus we omit it.

**Proposition 3.** The lengths of the bispecial words of the language \( L' \) are of the following form, with \( n, k \in \mathbb{N} \cup \{0\} \):

- **The lengths of the weak bispecial words** is of the form

\[
\begin{align*}
10k + 5 \\
10k + 7 \\
10k + 9 \\
10k + 11 \\
48.6^n(20k+24)+14(10k+7)−25(−1)^n(2k+1) \\
78.6^n(20k+16)+14(10k+3)+25(−1)^n(2k+1) \\
48.6^n(20k+16)+14(10k+3)−25(−1)^n(2k+3) \\
78.6^n(20k+24)+14(10k+7)+25(−1)^n(2k+3) \\
192.6^n+25(−1)^n−42 \\
312.6^n−25(−1)^n−42
\end{align*}
\]

- **The lengths of the strong bispecial words** is of the form

\[
\begin{align*}
4k + 2 \\
6k + 3 \\
8k + 4 \\
6k + 5 \\
8k + 8 \\
2k + 3 \\
18.6^n(20k+24)+14(10k+7)−5(−1)^n(2k+1) \\
48.6^n(20k+24)+14(10k+7)+10(−1)^n(2k+1) \\
18.6^n(20k+16)+14(10k+3)−5(−1)^n(2k+3) \\
48.6^n(20k+16)+14(10k+3)+10(−1)^n(2k+3) \\
4.18.6^n−42+5(−1)^n \\
4.8.6^n−42+10(−1)^n
\end{align*}
\]
Lemma 19. There exists $\beta > 0$ such that
\[
\sum_{i=0}^{N} b(i) \sim \beta N.
\]
Moreover we can give a formula for $\beta$:
\[
\beta = \frac{14}{15} + \sum_{n \geq 0} \left( \frac{7}{48.6^n \cdot 2 + 14 + 2(-1)^n} + \frac{7}{18.6^n \cdot 2 + 14 - (-1)^n} \right) - \sum_{n \geq 0} \left( \frac{7}{78.6^n \cdot 2 + 14 + 5(-1)^n} + \frac{7}{48.6^n \cdot 2 + 14 - 5(-1)^n} \right).
\]

Corollary 7. We deduce that $p(n) \sim \frac{\beta n^2}{2}$.

Proof. The proof is a direct consequence of Lemma 1 and Lemma 19. □

13 Regular decagon

In this short section we explain how to deal with the case of the regular decagon. In fact this case can be deduced easily from the case of the regular pentagon. In Figure 9 the lengths are not correct, but the angles have correct values. We have drawn the partition and its image by $\hat{T}$.

13.1 Induction

Lemma 20. The map $\hat{T}_{deca}$ is defined on five sets. The definitions of these sets are the following, see Figure 9 :

- The first set $V_1$ is a triangle, and $\hat{T}_{deca}$ is a rotation of angle $4\pi/5$ on this set.
- The second set $V_2$ is a quadrilateral, and $\hat{T}_{deca}$ is a rotation of angle $3\pi/5$ on this set.
- The third set is $V_3$ a quadrilateral, and $\hat{T}_{deca}$ is a rotation of angle $2\pi/5$ on this set.
- The fourth set $V_4$ is an infinite polygon with four edges, and $\hat{T}_{deca}$ is a rotation of angle $\pi/5$ on this set.
- The last one $V_5$ is a cone, and $\hat{T}_{deca}$ is a translation on this set.
Lemma 21. Consider the maps $\hat{T}_{\text{penta}}, \hat{T}_{\text{deca}}$ related to the outer billiard map outside the regular pentagon respectively the regular decagon. Then consider the induced map on $U_3$, and denote it by $\hat{T}_{\text{penta,3}}$. Then there exists a translation $s$ such that

$$\hat{T}_{\text{deca}} = s^{-1} \circ \hat{T}_{\text{penta,3}} \circ s.$$ 

The results follow from Lemma 21.

Corollary 8. There exists a bijective map $\theta$ between the coding of the decagon and the pentagon which is

$$\theta : \mathcal{L}'_{\text{deca}} \rightarrow \mathcal{L}'_{\text{penta}} \cap \rho(U_3)$$

$$\begin{array}{c}
1 \rightarrow \begin{array}{c}322222 \\
2 \rightarrow 3222 \\
3 \rightarrow 322 \\
4 \rightarrow 32 \\
5 \rightarrow 32
\end{array}
\end{array}$$

We use the same method as for the pentagon, and we deduce the language of the outer billiard map outside the regular decagon, and the complexity function.

References


