GEOMETRY AND MARKOфф’S SPECTRUM FOR $\mathbb{Q}(i)$, I

RYUJI ABE AND IAIN R. AITCHISON

Abstract. We develop a study of the relationship between geometry of geodesics and Markoff’s spectrum for $\mathbb{Q}(i)$. There exists a particular immersed totally geodesic twice punctured torus in the Borromean rings complement, which is a double cover of the once punctured torus having Fricke coordinates $(2\sqrt{2}, 2\sqrt{2}, 4)$. The set of the simple closed geodesics on this once punctured torus is decomposed into two subsets. The discrete part of Markoff’s spectrum for $\mathbb{Q}(i)$ (except for one) is given by the maximal Euclidean height of the lifts of the simple closed geodesics composing one of the subsets.

1. Introduction

Let $f(x, y) = ax^2 + bxy + cy^2$ be a binary indefinite quadratic form with real coefficients and with discriminant $D(f) = b^2 - 4ac$. We define

$$m(f) = \inf_{(x, y) \in \mathbb{Z}^2 \setminus \{(0, 0)\}} |f(x, y)|.$$

The set

$$\mathcal{M} = \left\{ \sqrt{D(f)} / m(f) \left| (a, b, c) \in \mathbb{R}^3, D(f) > 0 \right. \right\}$$

is called the Markoff spectrum for the rational number field $\mathbb{Q}$.

Let $\mathbb{Q}(i)$ denote the imaginary quadratic number field whose ring of integers is the set of Gaussian integers $\mathbb{Z}[i]$. The Markoff spectrum for $\mathbb{Q}(i)$ can be defined in the same way: for $f(x, y) = ax^2 + bxy + cy^2$,

$$\mathcal{M}_1 = \left\{ \sqrt{D(f)} / m_1(f) \left| (a, b, c) \in \mathbb{C}^3, D(f) \neq 0 \right. \right\},$$

where $m_1(f) = \inf_{(x, y) \in \mathbb{Z}[i]^2 \setminus \{(0, 0)\}} |f(x, y)|$.

In this paper we develop a study of the relationship between these spectra and geometry of geodesics.

We begin by giving a summary of the study of the Markoff spectrum for $\mathbb{Q}$, in particular, its characterization by geodesics on a once punctured torus. This becomes a model of our study of the Markoff spectrum for $\mathbb{Q}(i)$.

Markoff triples are triples of integers $(p, q, r)$ satisfying Markoff’s equation $p^2 + q^2 + r^2 = 3pqr$. We here suppose $1 \leq p \leq q \leq r$. The set of all Markoff triples is obtained by building the infinite binary tree: starting with $(1, 1, 1)$, the two children of any node $(p, q, r)$ is defined by $(p, r, 3pr - q)$ and $(q, r, 3qr - p)$ (exceptionally, $(1, 1, 1)$ and $(1, 1, 2)$ have only one child). The set of Markoff numbers

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\( K = \{1, 2, 5, 13, 29, \ldots \} \) which appear in these triples allows us to describe the discrete part of the Markoff spectrum for \( \mathbb{Q} \): \( \mathcal{M} \cap [0, 3) = \{ \sqrt{9 - (4/r^2)} \mid k \in K \} \). It is known that a minimal form attaining \( \sqrt{9 - (4/r^2)} \) is made from a Markoff triple \((p, q, r)\). (See [27], [28], and also [17].)

Let \( \mathbb{H}^2 = \{z = x + iy \in \mathbb{C} \mid y > 0\} \) be the upper half-plane endowed with the hyperbolic metric \( ds^2 = (dx^2 + dy^2)/y^2 \). Recall that a geodesic in \( \mathbb{H}^2 \) is a semicircle or a ray perpendicular to the real axis. The group \( \text{SL}(2, \mathbb{R}) \) acts on \( \mathbb{H}^2 \) as fractional linear transformations. It also acts on its boundary \( \mathbb{R} \cup \{\infty\} \). We always identify an element \( g \in \text{SL}(2, \mathbb{R}) \) with the fractional linear transformation induced by \( g \). If \( g \) fixes a unique point on the boundary of \( \mathbb{H}^2 \), it is called \textit{parabolic} and if it fixes a pair of distinct points on the boundary, it is called \textit{hyperbolic}. The geodesic in \( \mathbb{H}^2 \) fixed by a hyperbolic element \( g \) is called the \textit{axis} of \( g \).

Generally, if two elements \( g \) and \( h \) in \( \text{SL}(2, \mathbb{R}) \) are hyperbolic, their axes intersect, and \( h^{-1}g^{-1}hg \) is parabolic, then the quotient space of \( \mathbb{H}^2 \) by a Fuchsian group \( \langle g, h \rangle \) is identified with a once punctured torus. Setting \( X = \text{tr}(g), Y = \text{tr}(h), \) and \( Z = \text{tr}(gh) \), we know \( g \) and \( h \) are hyperbolic, their axes intersect, and \( h^{-1}g^{-1}hg \) is parabolic if and only if they satisfy \( X^2 + Y^2 + Z^2 = XYZ \) and all of \( X, Y, Z \) are greater than 2. Hence, the triples \((X, Y, Z)\) satisfying these conditions give coordinates of the Teichmüller space of the once punctured torus. This is first studied by R. Fricke in [20] (see also [23]); \( X^2 + Y^2 + Z^2 = XYZ \) is called Fricke’s moduli equation.

Let \( \langle A_3, B_3 \rangle \) be a free group generated by

\[
A_3 = \begin{pmatrix} 1 & 1 \\ 1 & 2 \end{pmatrix} \quad \text{and} \quad B_3 = \begin{pmatrix} 1 & -1 \\ -1 & 2 \end{pmatrix}.
\]

It has Fricke coordinates \((3, 3, 3)\) and the quotient space \( \mathbb{H}^2/\langle A_3, B_3 \rangle \) is a once punctured torus denoted by \( \mathbb{T}(A_3, B_3) \).

Observing the similarity between Fricke’s moduli equation and Markoff’s one (setting \( X = 3x, Y = 3y, \) and \( Z = 3z \) in Fricke’s, we get Markoff’s), H. Cohn began geometric study of the Markoff spectrum for \( \mathbb{Q} \). Recall that a matrix \( g \) is a \textit{generator} of \( \langle A_3, B_3 \rangle \) if there is another matrix \( h \) which generates \( \langle A_3, B_3 \rangle \) together with \( g \). Since generators of \( \langle A_3, B_3 \rangle \) have some special properties, defining a bijection between the set of Markoff numbers and a set of generators of \( \langle A_3, B_3 \rangle \), some theorems are obtained.

We define a form, for a matrix \( N = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \) given, by the fixed point equation of the action of \( N \): \( f_N(x, y) = cx^2 + (d-a)xy - by^2 \).

**Theorem 1.1** ([11]). For any \( \mu \) in the discrete part of \( \mathcal{M} \), there exists a generator \( N \) of \( \langle A_3, B_3 \rangle \) such that \( \mu = \sqrt{\text{det}(N)/m(f_N)} \) and \( m(f_N) = f_N(1, 0) \).

A geodesic on a quotient space of \( \mathbb{H}^2 \) is defined as the projection of a geodesic in \( \mathbb{H}^2 \). We say a geodesic is \textit{simple} if it has no self-intersections.

**Theorem 1.2** ([12]). A geodesic \( \gamma \) in \( \mathbb{H}^2 \) is the axis of a generator of \( \langle A_3, B_3 \rangle \) if and only if \( \gamma \) projects to a simple closed geodesic on the once punctured torus \( \mathbb{T}(A_3, B_3) \).

The \textit{Euclidean height} of a geodesic \( \gamma \) in \( \mathbb{H}^2 \) with endpoints \( \eta \) and \( \xi \) is defined as \( |\eta - \xi|/2 \) if \( \eta \) and \( \xi \) are finite or \( \infty \) otherwise. Denote this by \( h_E(\gamma) \). Let \( \gamma_{f_N} \) be a
geodesic whose endpoints are the solutions of $f_N(x, 1) = 0$, where $f_N$ is a minimal form in Theorem 1.1.

**Theorem 1.3** ([12]). The Euclidean height of $\gamma_{f_N}$ attains the maximum of the set \( \{ h_E(g(\gamma_{f_N})) \mid g \in \langle A_3, B_3 \rangle \} \) and $\sqrt{D(f_N)/m(f_N)} = 2h_E(\gamma_{f_N})$.

Finally, a theorem is deduced from these results:

**Theorem 1.4** (Cohn, see also [22]). The discrete part of the Markoff spectrum for $\mathbb{Q}$ is given by the twice maximal Euclidean height of the lifts of the simple closed geodesics on $\mathbb{T}_{\langle A_3, B_3 \rangle}$.

Since [11] such geometric study of the Markoff spectrum for $\mathbb{Q}$ has been developed by Cohn himself and by several authors (see [12], [15], [33], [24], [35], [8], [21], [34], etc.). The generators of $\langle A_3, B_3 \rangle$ which satisfy Theorems 1.1 and 1.2 are obtained by building inductively an infinite binary tree the nodes of which are triples of matrices in $\langle A_3, B_3 \rangle$ (see [13]). How to select an initial triple of matrices is important, because it must correspond to a good homotopy basis of $\mathbb{T}_{\langle A_3, B_3 \rangle}$.

There exist geometric studies of the other Markoff type spectra. For example, L.Ya.Vulakh proposed in [38] and [39], using the Klein model of the hyperbolic plane, a method of determining infinite binary trees of triples of matrices concerning the Markoff spectrum for a Fuchsian group.

The structure of the discrete part of the Markoff spectrum for $\mathbb{Q}(i)$ is investigated in [37] by Vulakh using binary complex quadratic forms. This is also studied by A.Schmidt from the point of view of Diophantine approximation of complex numbers based on the concept of the Farey tessellation ([31]). After these works, in this paper we call the discrete part of $\mathcal{M}_1$ Vulakh-Schmidt (VS) spectrum. Our aim is to give a geometric interpretation of this spectrum analogous to Theorem 1.4.

**Vulakh-Schmidt (VS) quadruples** are quadruples of positive integers $(x_1, x_2; y_1, y_2)$ satisfying Vulakh’s system of equations introduced in [37]:

\[
\begin{align*}
(1.2) & \quad \begin{cases}
x_1 + x_2 & = 2y_1y_2, \\
x_1x_2 & = y_1^2 + y_2^2.
\end{cases}
\end{align*}
\]

The set of all VS quadruples is obtained by building an infinite ternary tree (see §5.1). Let $\mathcal{N}(\Lambda) = \{1, 5, 29, 65, 169, \ldots\}$ be the set of $x_1$ and $x_2$ occurring in the VS quadruples and let $\mathcal{N}(M) = \{1, 3, 11, 17, 41, \ldots\}$ be the set of $y_1$ and $y_2$ occurring in them. The VS spectrum is described in the following way (see [37] and [31]):

\[
(1.3) \quad \left\{ \sqrt{4 - \frac{1}{\lambda^2}} \mid \lambda \in \mathcal{N}(\Lambda) \right\} \cup \left\{ \sqrt{\frac{3}{5} \sqrt{41}} \right\}.
\]

Let $\mathbb{H}^3 = \{ z + it \mid z = x + iy \in \mathbb{C}, t > 0 \}$ be the upper half-space endowed with the hyperbolic metric $ds^2 = (dx^2 + dy^2 + dt^2)/t^2$. Here we identify $(x, y, t) \in \mathbb{R}^3$ with the quaternion $x + iy + jt$. The group $\text{SL}(2, \mathbb{C})$ acts on $\mathbb{C} \cup \{ \infty \}$ as fractional linear transformations and acts on $\mathbb{H}^3$ as their Poincaré extensions.

The Picard group $\text{SL}(2, \mathbb{Z}[i])$ is a discrete subgroup of $\text{SL}(2, \mathbb{C})$ with finite covolume. There are various subgroups of the Picard group leading to quotient spaces of $\mathbb{H}^3$ related to links. Some of these are described in [40]. We focus our attention on the Borromean rings complement. It is obtained by gluing together two hyperbolic regular ideal octahedra. We define its geometric model in §3; it is represented as
a quotient space $\mathbb{H}^3/\Gamma$, where $\Gamma$ is a torsion-free normal subgroup of the Picard group with index 24.

We now introduce another once punctured torus. Let $\langle A_4, B_4 \rangle$ be a free group generated by
\begin{equation}
A_4 = \begin{pmatrix} 2\sqrt{2} & 1 \\ -1 & 0 \end{pmatrix} \quad \text{and} \quad B_4 = \begin{pmatrix} \sqrt{2} & 1 \\ 1 & \sqrt{2} \end{pmatrix}.
\end{equation}

This group has Fricke coordinates $(2\sqrt{2}, 2\sqrt{2}, 4)$ and the quotient space $\mathbb{H}^3/\langle A_4, B_4 \rangle$ is a once punctured torus denoted by $T_{\langle A_4, B_4 \rangle}$. This is involved in representing a particular twice punctured torus in the Borromean rings complement.

**Theorem 1.5.** There exists a hypersurface $\mathcal{HS}$ in the geometric model of the Borromean rings complement which is an immersed totally geodesic twice punctured torus conformally equivalent to a double cover of $T_{\langle A_4, B_4 \rangle}$.

This is suggested by the equations and the coordinates $(2\sqrt{2}, 2\sqrt{2}, 4)$. Vulakh’s system of equations is obtained from Fricke’s: setting $X = 4x, Y = 2\sqrt{2}y_1$, and $Z = 2\sqrt{2}y_2$, we get $2x^2 - 4y_1y_2x + (y_1^2 + y_2^2) = 0$ which is equivalent to Vulakh’s (see [38] and [39]). It is also obtained from Nakanishi-Näätänen’s equation (see [29]) which parametrizes the Teichmüller space of the twice punctured torus:
\[
\frac{d}{ae} + \frac{c}{bc} + \frac{e}{de} + \frac{a}{ce} + \frac{b}{ac} = \alpha
\]
by setting $e = 4x, a = c = 2\sqrt{2}y_1, b = d = 2\sqrt{2}y_2, \text{ and } \alpha = 2$.

From the point of view of the minimum of quadratic forms, Schmidt generalized in [33] Theorem 1.4 to all of the once punctured tori with different complex structures and discussed the case of $T_{\langle A_4, B_4 \rangle}$ as an example. He used Vulakh’s system of equations both in this example and in the study of the Markoff spectrum for $\mathbb{Q}(i)$ ([31]). This fact also suggests Theorem 1.5. A. Haas proved the same generalized result of Theorem 1.4 in [21] using geometric and topological arguments.

Theorem 1.5 is proved (see §2 and §4) conjugating $\langle A_4, B_4 \rangle$ to $\Gamma_o = \langle A, B \rangle$, where
\[
A = \frac{1}{\sqrt{2}} \begin{pmatrix} 5 & 7 \\ -1 & -1 \end{pmatrix} \quad \text{and} \quad B = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & 3 \end{pmatrix},
\]
and conjugating $\Gamma_o$ to $\tilde{\Gamma}_o = \langle \tilde{A}, \tilde{B} \rangle$, where
\[
\tilde{A} = \frac{1}{\sqrt{2}} \begin{pmatrix} 5 - i & -3 - 3i \\ -2i & -1 + i \end{pmatrix} \quad \text{and} \quad \tilde{B} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 + i & 1 - i \\ 2i & 3 - i \end{pmatrix}.
\]
Note that the group $\Gamma_o$ is not included in the modular group and that the group $\tilde{\Gamma}_o$ is not included in the Picard group. However, two conformally equivalent surfaces of $\mathcal{HS}$ obtained by these conjugates are represented as quotient spaces by subgroups of the modular group and the Picard group (see §2 and §4).

We propose in §5.2 an algorithm which gives a way of building an infinite ternary tree the nodes of which are quadruples of matrices in $\Gamma_o$ (see Algorithm VS). We take an initial quadruple of matrices corresponding to a homotopy basis $\{B, BA\}$ of the once punctured torus $T_o = \mathbb{H}^3/\Gamma_o$. We define two types of matrices $\Lambda_\chi$ and $M_m$ related to $\chi \in \mathcal{N}(A)$ and $m \in \mathcal{N}(M)$. The matrix $\Lambda_\chi$ is in $\text{SL}(2, \mathbb{Z})$ and $M_m$ is in $\text{SL}(2, \mathbb{Z}/\sqrt{2})$, and they have special forms (see Definition 5.2). The quadruples of matrices in the tree consist of two $\Lambda_\chi$’s and two $M_m$’s. These matrices are represented as words on $\{A, B\}$ and all of them are generators of $\Gamma_o$ (see Proposition
6.1). Analogizing to Theorem 1.2, we can prove that the axes of $\Lambda_\lambda$ and $M_m$ project to simple closed geodesics on the once punctured torus $\mathbb{T}_o$, conversely, the simple closed geodesics on $\mathbb{T}_o$ must be the projection of the axes of $\Lambda_\lambda$, $M_m$ and their equivalent matrices (see Theorem 6.4 and Corollary 6.8). By the form of matrices $\Lambda_\lambda$ and $M_m$, we can directly compute the Euclidean height of their axes.

The matrices $\tilde{\Lambda}_\lambda$ and $\tilde{M}_m$ in $\tilde{\Gamma}_o$ are defined as the conjugates of $\Lambda_\lambda$ and $M_m$ (see §5.3). The matrix $\tilde{\Lambda}_\lambda$ is in $\text{SL}(2, \mathbb{Z}[i])$ and $\tilde{M}_m$ is in $\text{SL}(2, \mathbb{Z}[i]/\sqrt{2})$ (see Definition 5.10). They are represented as words on $\tilde{A}, \tilde{B}$, $g$. All of them are generators of $\tilde{\Gamma}_o$ (see Proposition 6.9). The results on $\Lambda_\lambda$ and $M_m$ are translated to those on $\tilde{\Lambda}_\lambda$ and $\tilde{M}_m$. We are thus led to a theorem.

**Theorem 1.6.** For any $\mu$ in $\left\{ \sqrt{4 - 1/\lambda^2} \mid \lambda \in N(\Lambda) \right\}$, we constructively obtain a matrix $\tilde{\Lambda}_\lambda$ such that $\mu$ is equal to the twice Euclidean height of the axis of $\tilde{\Lambda}_\lambda$ and the axis projects to a simple closed geodesic on the hypersurface $\mathcal{HS}$ in the Borromean rings complement.

As an analogue of Theorem 1.4, we have

**Theorem 1.7.** Let $G(\Lambda)$ be a set of simple closed geodesics on $\mathcal{HS}$ whose lifts are the axes of $\tilde{\Lambda}_\lambda$, $\lambda \in N(\Lambda)$ and their equivalents. The VS spectrum (except for one) is given by the twice maximal Euclidean height of the lifts of the geodesics in $G(\Lambda)$.

We also obtain the following result as a by-product of building the ternary tree the nodes of which are quadruples of matrices. The set $\lambda \in N(\Lambda)$ gives a sequence of the Markoff spectrum $M$; the Euclidean height of the axis of $\Lambda_\lambda$, $\lambda \in N(\Lambda)$ corresponds to a value of $M$.

**Theorem 1.8.** For each $\mu = \sqrt{16 - (4/\lambda^2)}$, $\lambda \in N(\Lambda)$, there exists a matrix $\Lambda_\lambda$ in the tree such that $\mu = \sqrt{D(f_{\Lambda_\lambda})/m(f_{\Lambda_\lambda})}$ and $m(f_{\Lambda_\lambda}) = f_{\Lambda_\lambda}(1,0)$, moreover, $\mu = 2h_E(\gamma_{f_{\Lambda_\lambda}})$, where $f_{\Lambda_\lambda}$ is defined by the fixed point equation of the action of $\Lambda_\lambda$ and $\gamma_{f_{\Lambda_\lambda}}$ is a geodesic whose endpoints are its fixed points.

Since the values of $M$ in this theorem is bigger than 3, the sequence is included in the non-discrete part of $M$. We then conclude from Theorem 1.4 that the axis of $\Lambda_\lambda$ cannot project to a simple closed geodesic on the once punctured torus $\mathbb{T}_{(A_3, B_3)}$, while it projects to a simple closed one on $\mathbb{T}_o$.

The Markoff spectrum on sublattices of $\mathbb{Z}^2$, which is a subset of the classical Markoff spectrum $M$, has been studied. For definition and results, we refer the reader to [26] (also to [39] and [32]). The sequence in Theorem 1.8 coincides with such a spectrum on two disjoint (even and odd) sublattices of $\mathbb{Z}^2$. This suggests that we need the twice punctured torus to characterize geometrically the VS spectrum (the two sublattices correspond to the two punctures, see §6). It is asked in [26] why the Markoff spectrum on two disjoint sublattices of $\mathbb{Z}^2$ coincides with the VS spectrum (except for one) multiplied by two. The fact reflects some geometric regularity: the matrices which give geodesics corresponding to these spectra also coincide with each other up to conjugacy.

The paper is organized in the following way. We introduce in §2 some models of the once and twice punctured tori we need and define in §3 our geometric model of the Borromean rings complement. §4 is devoted to a proof of Theorem 1.5. The
infinite ternary trees the nodes of which are VS quadruples, quadruples of $\Lambda_\lambda$'s and $M_\mu$'s, and quadruples of $\tilde{\Lambda}_\lambda$'s and $\tilde{M}_\mu$'s are defined in §5.1, §5.2, and §5.3, respectively. One of the most important parts of this paper is §7 in which we prove that these trees and the matrices are well-defined. Using properties of matrices $\Lambda_\lambda$ and $\tilde{\Lambda}_\lambda$, Theorems 1.6 and 1.7 are proved in §6.

Before ending the introduction, we give some additional comments.

In this paper, after Cohn’s idea (see the preliminary remarks of [14]), we use the designation “Markoff” to refer to A.A. Markoff (1856-1922) as the number-theorist. His name is customarily spelled “Markov” as the probabilist.

We can regard a triple $(X, Y, Z)$ satisfying Fricke’s equation as a representation of the free group on two generators into $\text{SL}(2, \mathbb{R})$ with the property that the commutator has trace equal to $-2$. Solving the equation over the complex numbers, we can consider representations into $\text{SL}(2, \mathbb{C})$ having the same property. In this context, the equation is written by $x^2 + y^2 + z^2 = xyz$ and is called the “Markoff equation” (see [10] and [6]).

McShane’s identity is an identity concerning the length of simple closed geodesics on a once punctured torus and is universal for all elements in the Teichmüller space of the once punctured torus. Together with the generalization of Theorem 1.4 by Haas and Schmidt, it is one of the most spectacular results about simple closed geodesics on a once punctured torus and its Teichmüller space.

What is interesting for us is Bowditch’s alternative proof of McShane’s identity using tree of “Markoff triples”. Since the traces of matrices give hyperbolic lengths of their axes, it can be interpreted as an identity concerning the traces of a representation. Hence, considering complex “Markoff triples”, McShane’s identity extends to that of quasifuchsian representations (see [9]). In this setting, we will discuss Vulakh’s equation in a forthcoming paper.

2. Hecke groups, once and twice punctured tori

Let $\mathbb{H}^2 = \{ z = x + iy \mid y > 0 \}$ be the upper half-plane endowed with the hyperbolic metric $ds^2 = (dx^2 + dy^2)/y^2$. A geodesic in $\mathbb{H}^2$ is a semicircle or a ray perpendicular to the real axis. The group $\text{SL}(2, \mathbb{R})$ acts on $\mathbb{H}^2$ as fractional linear transformations. It also acts on its boundary $\mathbb{R} \cup \{ \infty \}$. We always identify an element $g$ of $\text{SL}(2, \mathbb{R})$ with the fractional linear transformation induced by $g$. Recall that an element $g$ of $\text{SL}(2, \mathbb{R})$ is parabolic if $g$ has a unique fixed point on $\mathbb{R} \cup \{ \infty \}$ and that $g$ is hyperbolic if $g$ has two fixed points on it. They are equivalent to $|\text{tr}(g)| = 2$ and $|\text{tr}(g)| > 2$, respectively.

Hecke groups are the groups generated by two elements

$$G_q = \left\langle \begin{pmatrix} 1 & 2\cos(\pi/q) \\ 0 & 1 \end{pmatrix}, \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \right\rangle$$

for integers $q \geq 3$. When $q = 3$, we simply have $\text{SL}(2, \mathbb{Z})$. We use both $G_3$ and $G_4$ in our discussion.

Let $\langle A_3, B_3 \rangle$ be a free group generated by $A_3$ and $B_3$ of (1.1). These matrices are hyperbolic; the map $A_3$ sends $\infty$ to 1 and $-1$ to 0; the map $B_3$ sends $\infty$ to $-1$ and 1 to 0. Gluing the vertical ray $\text{Re}(z) = -1$ to the semicircle sending 0 and 1 by $A_3$, and the vertical ray $\text{Re}(z) = 1$ to the semicircle sending 0 and $-1$ by $B_3$, we obtain a fundamental domain of $\langle A_3, B_3 \rangle$. The quotient space $\mathbb{H}^2/\langle A_3, B_3 \rangle$ is
thus a once punctured torus, denoted by $T_{(A_3, B_3)}$. Using a well-known fundamental domain of the modular group, we can verify that the once punctured torus $T_{(A_3, B_3)}$ is a six-fold cover of the modular surface. From the point of view of group, $(A_3, B_3)$ is a torsion-free normal subgroup of the modular group with index 6.

Let $(A_4, B_4)$ be a free group generated by $A_4$ and $B_4$ of (1.4). They are also hyperbolic; the map $A_4$ sends 0 to $\infty$ and $-1/\sqrt{2}$ to $-\sqrt{2}$; the map $B_4$ sends $-\sqrt{2}$ to $\infty$ and $-1/\sqrt{2}$ to 0. We obtain a fundamental domain of $(A_4, B_4)$ gluing the semicircle sending $-1/\sqrt{2}$ and 0 to the vertical ray $\Re(z) = -\sqrt{2}$ by $A_4$, and the semicircle sending $-\sqrt{2}$ and $-1/\sqrt{2}$ to the vertical ray $\Re(z) = 0$ by $B_4$. Note that this domain is a four-fold cover of a typical fundamental domain $F_4$ of $G_4$:

$$F_4 = \left\{ z = x + iy \in \mathbb{H}^2 \left| \frac{1}{\sqrt{2}} \leq x \leq \frac{1}{\sqrt{2}} \right. \right\}.$$

The quotient space $\mathbb{H}^2/(A_4, B_4)$ is also a once punctured torus, denoted by $T_{(A_4, B_4)}$. In this case, $(A_4, B_4)$ is a torsion-free normal subgroup of the Hecke group $G_4$ with index 4.

Consider a free group $(g, h)$ generated by $g, h \in \text{SL}(2, \mathbb{R})$, assuming that $g$ and $h$ are hyperbolic, their axes intersect, and the commutator $[h, g]$ is parabolic. In general, the quotient space $\mathbb{H}^2/(g, h)$ is a once punctured torus. Set $X = \text{tr}(g)$, $Y = \text{tr}(h)$, and $Z = \text{tr}(gh)$. The condition that $g$ and $h$ are hyperbolic, their axes intersect, and $[h, g]$ is parabolic is equivalent to the condition that they satisfy $X^2 + Y^2 + Z^2 = XYZ$ and all of $X, Y, Z$ are greater than 2. Such triples $(X, Y, Z)$, therefore, provide coordinates of the Teichmüller space of the once punctured torus ([20], [23]). Note that $(A_3, B_3)$ is represented by $(3, 3, 3)$ and $(A_4, B_4)$ by $(2\sqrt{2}, 2\sqrt{2}, 4)$.

If we abelianize such a group $(g, h)$, then the commutator $[h, g]$ becomes the identity (geometrically, the cusp of the quotient space disappears). We thus have the closed torus corresponding to a once punctured torus. Let 1, $\rho = e^{2\pi i}$, and $i$ denote, respectively, the following three translations on $\mathbb{C}$: $z \mapsto z + 1$, $z \mapsto z + \rho$, and $z \mapsto z + i$. The groups $(1, \rho)$ and $(1, i)$ are abelian; the quotient spaces $\mathbb{C}/(1, \rho)$ and $\mathbb{C}/(1, i)$ are closed flat tori. The former is a torus consisting of two regular triangles and the latter is by a square. We can define an explicit conformal mapping $\varphi_3$ from $T_{(A_3, B_3)}$ to $\mathbb{C}/(1, \rho)$ so that it gives identification of $A_3$ with $\rho$ and of $B_3$ with 1.

We can also define an explicit conformal mapping $\varphi_4$ between $T_{(A_4, B_4)}$ and $\mathbb{C}/(1, i)$, identifying $A_4$ with $i$ and $B_4$ with 1. (See [11], [16], and [1].) The construction of these conformal mappings means the abelianization of the groups $(A_3, B_3)$ and $(A_4, B_4)$. The identification of generators given by $\varphi_3$ and $\varphi_4$ allows us to conclude that the once punctured torus $T_{(A_3, B_3)}$ and $T_{(A_4, B_4)}$ possess the highest and the second highest degree of symmetry in the Teichmüller space of the once punctured torus.

Let $(P_4, Q_4, R_4)$ be a group generated by

$$P_4 = \begin{pmatrix} 1 & \sqrt{2} \\ \sqrt{2} & 3 \end{pmatrix}, \quad Q_4 = \begin{pmatrix} 1 & -\sqrt{2} \\ -\sqrt{2} & 3 \end{pmatrix}, \quad R_4 = \begin{pmatrix} 3 & 2\sqrt{2} \\ 2\sqrt{2} & 3 \end{pmatrix}.$$

These matrices are hyperbolic and satisfy the following relations:

$$P_4 = B_4 A_4^{-1}, \quad Q_4 = A_4^{-1} B_4^{-1}, \quad R_4 = B_4^2, \quad Q_4 P_4 = A_4^{-2}.$$
We show a fundamental domain of \( \langle P_4, Q_4, R_4 \rangle \). In Figure 1 we set

\[
\begin{align*}
p_0 &= \infty, \quad p_1 = -2\sqrt{2}, \quad p_2 = -\sqrt{2}, \quad p_3 = -\frac{1}{\sqrt{2}}, \\
p_4 &= 0, \quad p_5 = \frac{1}{\sqrt{2}}, \quad p_6 = \sqrt{2}, \quad p_7 = 2\sqrt{2}.
\end{align*}
\]

Observe how \( P_4, Q_4, \) and \( R_4 \) send points:

\[
P_4 : p_0 \mapsto p_5, \quad p_1 \mapsto p_6, \quad p_2 \mapsto p_4, \quad Q_4 : p_0 \mapsto p_3, \quad p_6 \mapsto p_4, \quad p_7 \mapsto p_2, \\
R_4 : p_2 \mapsto p_6, \quad p_3 \mapsto p_5.
\]

We can glue the vertical ray \((p_2 \to p_0)\) to the semicircle \((p_4 \to p_5)\) by \( P_4 \), the vertical ray \((p_6 \to p_0)\) to the semicircle \((p_4 \to p_3)\) by \( Q_4 \), and the semicircle \((p_2 \to p_3)\) to the one \((p_6 \to p_5)\) by \( R_4 \). A fundamental domain of \( \langle P_4, Q_4, R_4 \rangle \) is thus obtained (see Figure 1). The quotient space \( \mathbb{H}^2/\langle P_4, Q_4, R_4 \rangle \) is then a twice punctured torus, denoted by \( \mathbb{T}(P_4, Q_4, R_4) \). Note that in this setting the fundamental domain of \( \langle A_4, B_4 \rangle \) introduced above is obtained by gluing the vertical ray \((p_2 \to p_0)\) to the semicircle \((p_3 \to p_4)\) by \( B_4 \), and the vertical ray \((p_4 \to p_6)\) with the semicircle \((p_3 \to p_2)\) by \( A_4 \).

**Proposition 2.1.** The twice punctured torus \( \mathbb{T}(P_4, Q_4, R_4) \) is a two-fold cover of the once punctured torus \( \mathbb{T}(A_4, B_4) \). In other words, the group \( \langle P_4, Q_4, R_4 \rangle \) is a subgroup of \( \langle A_4, B_4 \rangle \) with index 2. The group \( \langle P_4, Q_4, R_4 \rangle \) is, therefore, a subgroup of \( G_4 \) with index 8.

**Proof.** These are deduced from (2.3) and (2.1). \( \square \)

Let us show another fundamental domain of \( \langle P_4, Q_4, R_4 \rangle \). It follows from (2.3) that the geodesic going from \( p_1 \) to \( p_2 \) is glued to the one from \( p_6 \) to \( p_4 \) by \( P_4 \) and that the geodesic going from \( p_6 \) to \( p_7 \) is glued to the one from \( p_4 \) to \( p_2 \) by \( Q_4 \). Moreover, the vertical ray \( \text{Re}(z) = p_1 \) is glued to the one \( \text{Re}(z) = p_7 \) by the map

\[
Q_4^{-1}R_4^{-1}P_4 = B_4A_4B_4^{-1}A_4^{-1} = \begin{pmatrix} -1 & -4\sqrt{2} \\ 0 & -1 \end{pmatrix}.
\]

We thus obtain another fundamental domain of \( \langle P_4, Q_4, R_4 \rangle \) (see Figure 1).
We now conjugate \( \langle A_4, B_4 \rangle \) and \( \langle P_4, Q_4, R_4 \rangle \) by a matrix \( U = \left( \begin{array}{cc} \sqrt{2} & -1 \\ 0 & 1 \end{array} \right) \). The conjugate of the former is a group \( \Gamma_o = \langle A, B \rangle \) generated by
\[
A = UA_4U^{-1} = \frac{1}{\sqrt{2}} \left( \begin{array}{cc} 5 & 7 \\ -1 & -1 \end{array} \right) \quad \text{and} \quad B = UB_4U^{-1} = \frac{1}{\sqrt{2}} \left( \begin{array}{cc} 1 & 1 \\ 1 & 3 \end{array} \right);
\]
that of the latter is a group \( \Gamma_t = \langle P, Q, R \rangle \) generated by
\[
P = UP_4U^{-1} = \left( \begin{array}{cc} 0 & -1 \\ 1 & 4 \end{array} \right), \quad Q = UQ_4U^{-1} = \left( \begin{array}{cc} 2 & -3 \\ -1 & 2 \end{array} \right),
\]
\[
R = UR_4U^{-1} = \left( \begin{array}{cc} 1 & 2 \\ 2 & 5 \end{array} \right).
\]
Note that \( U \) was taken so that \( \Gamma_t \) becomes a subgroup of the modular group (see Proposition 2.2).

Since the translation by \( U \) is conformal, the quotient space \( T_o = \mathbb{H}^2/\Gamma_o \) is conformally equivalent to \( T_{\langle A_4, B_4 \rangle} \), and \( T_t = \mathbb{H}^2/\Gamma_t \) is to \( T_{\langle P_4, Q_4, R_4 \rangle} \). In Figure 1 we now set
\[
p_0 = \infty, \quad p_1 = -5, \quad p_2 = -3, \quad p_3 = -2, \quad p_4 = -1, \quad p_5 = 0, \quad p_6 = 1, \quad p_7 = 3.
\]
These are the images by \( U \) of the points in (2.2). Using the same gluing patterns as before, we obtain representation of the quotient spaces \( T_o \) and \( T_t \).

**Proposition 2.2.** The group \( \Gamma_t \) is a subgroup of the modular group with index 12.

**Proof.** We can directly verify that a fundamental domain of \( \Gamma_t \) is a 12-fold cover of the well-known fundamental domain of the modular group. □

3. **Model of the Borromean rings complement**

Let \( \mathbb{H}^3 = \{ z + jt \mid z = x + iy \in \mathbb{C}, \ t > 0 \} \) be the upper half-space endowed with the hyperbolic metric \( ds^2 = (dx^2 + dy^2 + dt^2)/t^2 \). Here we identify \( (x, y, t) \in \mathbb{R}^3 \) with the quaternion \( x + iy + jt \) (for this expression, we refer the reader to [7]). A geodesic in \( \mathbb{H}^3 \) is a semicircle or a ray perpendicular to the complex plane \( \mathbb{C} \). The group \( \text{SL}(2, \mathbb{C}) \) acts on \( \mathbb{C} \cup \{ \infty \} \) as fractional linear transformations and acts on \( \mathbb{H}^3 \) as their Poincaré extensions. Note that \( \mathbb{C} \cup \{ \infty \} \) is the boundary of \( \mathbb{H}^3 \). We always identify an element \( g \in \text{SL}(2, \mathbb{C}) \) with the fractional linear transformation and its Poincaré extension induced by \( g \). Recall that an element \( g \in \text{SL}(2, \mathbb{C}) \) is parabolic if \( g \) has a unique fixed point on the boundary of \( \mathbb{H}^3 \) and \( g \) is loxodromic if \( g \) has two fixed points on it. The former is equivalent to \( \text{tr}^2(g) = 4 \). Loxodromic elements split into two cases: \( g \) is hyperbolic if \( \text{tr}^2(g) \in (4, +\infty) \); \( g \) is strictly loxodromic if \( \text{tr}^2(g) \notin [0, +\infty) \) ([7]).

The group defined as
\[
\text{SL}(2, \mathbb{Z}[i]) = \left\{ \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \mid \alpha, \beta, \gamma, \delta \in \mathbb{Z}[i], \ \alpha \delta - \beta \gamma = 1 \right\}
\]
is called the Picard group, where \( \mathbb{Z}[i] \) is the set of Gaussian integers. The Picard group is a discrete subgroup of \( \text{SL}(2, \mathbb{C}) \) with finite covolume. A fundamental region of \( \text{SL}(2, \mathbb{Z}[i]) \) is described as follows:
\[
\left\{ x + iy + jt \in \mathbb{H}^3 \mid x^2 + y^2 + t^2 \geq 1, \ |x| \leq \frac{1}{2}, \ 0 \leq y \leq \frac{1}{2} \right\}.
\]
It has a single parabolic vertex at \( \infty \). It is also known that the Picard group is generated by the four elements:

\[
S = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, \quad T = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}, \quad U = \begin{pmatrix} 1 & i \\ 0 & 1 \end{pmatrix}, \quad L = \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix}
\]

(see [18]). Note that \( S \) and \( T \) generate \( \text{SL}(2, \mathbb{Z}) \).

Analogous to the Farey tessellation (i.e., a tiling of the upper half-plane by ideal regular hyperbolic triangles), the upper half-space \( \mathbb{H}^3 \) is tiled by the images of a hyperbolic regular ideal octahedron under the action of the Picard group.

We introduce some parts of planes and hemispheres in \( \mathbb{H}^3 \):

\[
S_1 = \left\{ x + iy + jt \in \mathbb{H}^3 \mid x^2 + (y - \frac{1}{2})^2 + t^2 \geq \frac{1}{4}, x = 0, 0 \leq y \leq 1 \right\},
\]

\[
S_2 = \left\{ x + iy + jt \in \mathbb{H}^3 \mid (x - \frac{1}{2})^2 + y^2 + t^2 \geq \frac{1}{4}, y = 0, 0 \leq x \leq 1 \right\},
\]

\[
S_5 = \left\{ x + iy + jt \in \mathbb{H}^3 \mid x^2 + (y - \frac{1}{2})^2 + t^2 = \frac{1}{4}, x + y \leq 1, x - y \leq 0, x \geq 0 \right\},
\]

\[
S_6 = \left\{ x + iy + jt \in \mathbb{H}^3 \mid (x - \frac{1}{2})^2 + y^2 + t^2 = \frac{1}{4}, x + y \leq 1, x - y \geq 0, y \geq 0 \right\},
\]

\[
S_3 = TS_1, \quad S_4 = US_2, \quad S_7 = TULS_5, \quad S_8 = TULS_6.
\]

Let \( \Delta \) denote the hyperbolic regular ideal octahedron determined by the eight faces \( S_k, k = 1 \) to 8 (see a sketch in Figure 2). We call \( S_r, r = 1 \) to 4 upper faces of \( \Delta \) and \( S_r, r = 5 \) to 8 lower faces of \( \Delta \). We sometimes illustrate \( \Delta \) as in Figure 3. The tessellation of \( \mathbb{H}^3 \) by the hyperbolic regular ideal octahedra is defined as \( \mathcal{F}^3 = \{ g\Delta \mid g \in \text{SL}(2, \mathbb{Z}[i]) \} \).

Some examples of hyperbolic 3-manifolds of finite volume are obtained by gluing together a finite number of regular ideal polyhedra in \( \mathbb{H}^3 \) along their sides. In many cases, such an example is homeomorphic to the complement of a knot or link in the 3-ball. (See [36] and [30].) Here we recall a gluing pattern for the Borromean rings complement after [36], [3], [4], and [5].
Figure 3. Illustration of the hyperbolic regular ideal octahedron \( \Delta \). The upper faces are hyperbolic triangles in the vertical planes \( x = 0 \), \( x = 1 \), \( y = 0 \), and \( y = 1 \). The lower faces are isosceles triangles on the hemispheres of the radius \( 1/2 \) with the centers \( 1/2 \), \( i/2 \), \( U(1/2) \), and \( T(i/2) \).

Figure 4. Two planar Borromean rings topologically regarded as two octahedra.

Three rings in the left side of Figure 4 are a planar representation of the Borromean rings. Since they decompose the plane into eight regions, the picture is topologically regarded as an octahedron, denoted by \( \Pi^+ \). If we associate a + sign to white and a – sign to black in the figure, then \( \Pi^+ \) is 2-colored in checker-board fashion. Take an identical copy of \( \Pi^+ \), reverse all signs (and colors), and denote the resulting octahedron by \( \Pi^- \) (see the right side of Figure 4).

Taking the truncation of \( \Pi^\pm \), we get the truncated octahedra bounded by six squares and eight hexagons, denoted by \( \Pi^\pm_t \). They are illustrated in Figure 5. The six squares of \( \Pi^+_t \) correspond to cuts of the vertices of \( \Pi^\pm \). We attach labels \( a_i, b_i \),

\[
\begin{align*}
\Pi^+ & : & & c_1 & & b_2 & + & c_4 & & b_1 \\
& & - & a_3 & & & - & & & \\
& & + & b_3 & & c_3 & + & & & \\
& & & c_2 & & b_4 & & + & a_1 & \\
\Pi^- & : & & c_1 & & a_2 & - & c_3 & & a_1 \\
& & + & b_4 & & & + & & & \\
& & - & a_3 & & b_4 & - & & & \\
& & & b_2 & & c_2 & & + & c_1 & \\
\end{align*}
\]
Table 1. The information for $\Pi^\pm$ and $\Pi_l^\pm$

<table>
<thead>
<tr>
<th>$r$</th>
<th>$\sigma_r^+$ labels for the sides of $\phi_r^+$</th>
<th>$\sigma_r^-$ labels for the sides of $\phi_r^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$a_1b_1c_1$</td>
<td>$a_2b_1c_4$</td>
</tr>
<tr>
<td>2</td>
<td>$a_1b_1c_1$</td>
<td>$a_1b_1c_1$</td>
</tr>
<tr>
<td>3</td>
<td>$a_1b_2c_2$</td>
<td>$a_4b_2c_1$</td>
</tr>
<tr>
<td>4</td>
<td>$a_4b_3c_2$</td>
<td>$a_3b_2c_4$</td>
</tr>
<tr>
<td>5</td>
<td>$a_3b_2c_4$</td>
<td>$a_2b_4c_3$</td>
</tr>
<tr>
<td>6</td>
<td>$a_2b_1c_4$</td>
<td>$a_1b_4c_2$</td>
</tr>
<tr>
<td>7</td>
<td>$a_2b_4c_3$</td>
<td>$a_4b_3c_2$</td>
</tr>
<tr>
<td>8</td>
<td>$a_3b_3c_3$</td>
<td>$a_3b_3c_3$</td>
</tr>
</tbody>
</table>

Figure 5. Two truncated octahedra corresponding to $\Pi^+$ and $\Pi^-$

and $c_l$ ($l = 1$ to 4) to the four parts of each rings of $\Pi^+$, and to those of $\Pi^-$ by rotating the three rings by $2\pi/3$. The same labels are attached to the corresponding edges of $\Pi_l^+$ and $\Pi_l^-$. (See Figures 4 and 5.) We also attach labels $\phi_r^\pm$ ($r = 1$ to 8) to the eight faces of $\Pi^\pm$ and $\Pi_l^\pm$. Each face $\phi_r^\pm$ in $\Pi^\pm$ is a triangle with sign allocation $\sigma_r^\pm$ (black or white). The signs of the faces are depicted in Figure 4 and the names of the faces $\phi_r^\pm$ are depicted in Figure 5. The correspondence between the faces of $\Pi^\pm$ and $\Pi_l^\pm$ are clearly obtained from the labels $a_l$, $b_l$, $c_l$ of edges. The information for $\Pi^\pm$ and $\Pi_l^\pm$ are summarized in Table 1. Note that $\sigma_l^\pm$ and $\sigma_r^-$ have the opposite signs.

We glue $\phi_r^+$ with the corresponding face $\phi_r^-$ by a rotation of $2\pi\sigma_r^\pm/3$, where the sign (+ or −) means the clockwise or anticlockwise direction. The three edges of each triangle always have labels $a_{s_k}$, $b_{s_k}$, and $c_{s_k}$, where $s_k$, $k = 1, 2, 3$ stand for some integers between 1 and 4 (see Table 1). The gluing of $\phi_r^+$ with $\phi_r^-$ by rotation is equivalent to gluing them together by identifying their edges with labels $a_{s_k}$, $b_{s_k}$, and $c_{s_k}$. For example, $\phi_1^+$ and $\phi_1^-$ are glued by identifying $a_4$, $b_2$, and $c_1$ with $a_2$, $b_1$, and $c_4$, respectively.
We denote the resulting topological space by $\overline{M}_{BR}$. Denote also by $M_{BR}$ the topological space deleting vertices from $\overline{M}_{BR}$. The space $M_{BR}$ is equal to a topological space obtained by the same gluing of the truncated octahedra $\Pi^\pm$. Then it is known that $M_{BR}$ is canonically homeomorphic to $S^3 \setminus L$, where $L$ denotes the Borromean rings. The space $M_{BR}$ is called the Borromean rings complement.

We now make a geometric model of the Borromean rings complement from the two adjacent hyperbolic regular ideal octahedra $\Delta$ and $U^{-1}\Delta$. Denoting $U^{-1}S_r = S'_r \ (r = 1 \text{ to } 8)$, we illustrate them as in Figure 6. Looking at the truncated octahedra $\Pi^\pm$ depicted in Figure 5, we take correspondence between each face $S_r$ of $\Delta$ and each $\phi^+_r$ of $\Pi^\pm$. Then the ideal vertices of $\Delta$ ($\infty$, 0, $i$, $1 + i$, and $(1 + i)/2$) correspond to six squares of $\Pi^\pm$. Comparing Figures 5 and 6, we get the correspondence illustrated in the upper part of Figure 7. From the gluing pattern for making $M_{BR}$, identifying $\phi^+_2$ with $\phi^-_2$, we obtain the following correspondence between the faces $S'_r$ of $U^{-1}\Delta$ and $\phi^-_r$ of $\Pi^-_r$:

$\phi^+_1 \leftrightarrow S'_3, \ \phi^+_2 \leftrightarrow S'_2 = S'_1, \ \phi^+_3 \leftrightarrow S'_8, \ \phi^+_4 \leftrightarrow S'_7, \ \phi^+_5 \leftrightarrow S'_6, \ \phi^+_6 \leftrightarrow S'_1, \ \phi^+_7 \leftrightarrow S'_5, \ \phi^+_8 \leftrightarrow S'_0.$

It is illustrated in the lower part of Figure 7. We now get the gluing pattern for $\Delta$ and $U^{-1}\Delta$:

$$S_1 \leftrightarrow S'_3, \ S_3 \leftrightarrow S'_4, \ S_4 \leftrightarrow S'_7, \ S_6 \leftrightarrow S'_3, \ S_9 \leftrightarrow S'_1, \ S_7 \leftrightarrow S'_5, \ S_5 \leftrightarrow S'_6.$$  

(3.1)

(see Figure 6). Note that we have obtained not only the correspondence of the faces between $\Delta$ and $U^{-1}\Delta$ but also that of the vertices and the edges of each face. For
example, the ideal vertices 0, i, and \( \infty \) of \( S_1 \) are identified with \( 1 - i, 1 \), and \( \infty \) of \( S_3 \), respectively (see Figure 7).

**Remark 3.1.** Consider the set of the images of \( \Delta \) by translations of the group generated by \( T \) and \( U \). Applying the preceding argument to any two adjacent hyperbolic regular ideal octahedra in this set, we obtain the gluing pattern for them. We illustrate in Figure 8 a part of the gluing pattern of the images of the lower faces of \( \Delta \). The gluing pattern of the images of the upper faces is obtained from Figures 8 and 9. Gluing \( \phi^+ \) and \( \phi^- \) of any two adjacent hyperbolic regular ideal octahedra, we can construct a geometric model of the Borromean rings complement.

In Figure 8, we can find a combinatorial structure of the cusp \( \infty \) of the Borromean rings complement: the link of the cusp \( \infty \) (i.e., the surface around \( \infty \) obtained by gluing together the two hyperbolic regular ideal octahedra \( \Delta \) and \( U^{-1}\Delta \)) is a torus consisting of four unit squares. For example, the four unit squares \( \{x + iy \mid 0 \leq x \leq 4 \text{ and } 1 \leq y \leq 2\} \) make a periodic pattern in Figure 8.

By the definition of the tessellation \( \mathcal{K}^3 \) of \( \mathbb{H}^3 \), the faces of \( \Delta \) and \( U^{-1}\Delta \) must be glued by some actions of the Picard group.

**Proposition 3.2.** The gluing pattern (3.1) of the faces of \( \Delta \) and \( U^{-1}\Delta \) is represented by

\[
P_\infty = \begin{pmatrix} 1 & 1 - i \\ 0 & 1 \end{pmatrix}, \quad P_0 = \begin{pmatrix} 1 & 0 \\ -1 + i & 1 \end{pmatrix}, \quad P_1 = \begin{pmatrix} i & 1 - i \\ -1 + i & 2 - i \end{pmatrix}
\]
Figure 8. A part of the gluing pattern of the images of the lower faces of $\Delta$. Each unit square the vertices of which are points of Gaussian integers is an image of the lower faces of $\Delta$. We can find the lower part of Figure 7 in the left-bottom corner.

Figure 9. Four patterns of labeling of a hyperbolic regular ideal octahedron
in the following way:

\[ P_\infty : S_1 \rightarrow S'_3, \quad P_0 : S_6 \rightarrow S'_1, \quad P_1 : S_8 \rightarrow S'_2, \]
\[ P_2 = P_1 P_\infty : S_4 \rightarrow S'_5, \quad P_3 = P_\infty P_0 : S_8 \rightarrow S'_2, \]
\[ P_4 = P_0 P_1 : S_7 \rightarrow S'_5, \quad P_5 = P_\infty P_0 (P_\infty^{-1} P_1 P_\infty) = P_1 P_\infty (P_1^{-1} P_0 P_1) : S_8 \rightarrow S'_0. \]

**Proof.** These are verified by direct calculations.

For example, \( P_\infty \) sends \( 0, i, \) and \( \infty \) of \( S_1 \) to \( 1-i, 1, \) and \( \infty \) of \( S'_3 \), respectively. \( \square \)

**Remark 3.3.** The actions \( P_\infty, P_0, \) and \( P_1 \) are parabolic, \( P_2, P_3, \) and \( P_4 \) are strictly loxodromic, and \( P_5 \) is hyperbolic.

**Proposition 3.4.** The actions \( P_1^{-1} P_0 P_1 P_0^{-1}, P_\infty^{-1} P_1 P_\infty P_1^{-1}, \) and \( P_0^{-1} P_\infty P_0 P_\infty^{-1} \) are parabolic. Moreover, they have the same fixed points \( \infty, 0, \) and \( 1 \) as \( P_\infty, P_0, \) and \( P_1 \), respectively.

**Proof.** These are also verified by direct calculations.

For example, \( P_1^{-1} P_0 P_1 P_0^{-1} = \begin{pmatrix} -1 & -2 - 2i \\ 0 & -1 \end{pmatrix} \) is parabolic and has the fixed point \( \infty \) which is the same as \( P_\infty. \) \( \square \)

Hence, the geometric model of the Borromean rings complement by \( \Delta \) and \( U^{-1} \Delta \) has the three cusps \( \infty, 0, \) and \( 1; \) the links of them are tori. Moreover, \( P_\infty \) and \( P_1^{-1} P_0 P_1 P_0^{-1} \) (\( P_0 \) and \( P_\infty^{-1} P_1 P_\infty P_1^{-1} \)) are transformations corresponding to a meridian and a longitude of the torus. The translations \( P_\infty \) and \( P_1^{-1} P_0 P_1 P_0^{-1} \) are indicated in Figure 8 by two arrows. They span a rectangle which also makes a periodic pattern in the figure (compare Remark 3.1).

We finally deduce a conclusion from the preceding discussion:

**Theorem 3.5.** The quotient space \( \text{BRC} = \mathbb{H}^3 / \Gamma_{\text{BR}} \) is a geometric model of the Borromean rings complement, where

\[ \Gamma_{\text{BR}} = \left\{ P_\infty, P_0, P_1 \mid P_\infty (P_1^{-1} P_0 P_1 P_0^{-1}) = (P_1^{-1} P_0 P_1 P_0^{-1}) P_\infty, \right. \]
\[ \left. P_0 (P_\infty^{-1} P_1 P_\infty P_1^{-1}) = (P_\infty^{-1} P_1 P_\infty P_1^{-1}) P_0, \right. \]
\[ \left. P_1 (P_0^{-1} P_\infty P_0 P_\infty^{-1}) = (P_0^{-1} P_\infty P_0 P_\infty^{-1}) P_1 \right\}. \]

**Remark 3.6.** N.Wielenberg investigated in [40], using an HNN extension, a subgroup of the Picard group the corresponding link of which is the Borromean rings. His result is a little different from ours.

4. **Hypersurface in BRC**

We continue a discussion on the geometric model of the Borromean rings complement. We take the following planes in \( \mathbb{H}^3 \) perpendicular to \( \mathbb{C} \):

\[ W_1 = \left\{ \frac{1}{2} + y i + t j \mid (y, t) \in \mathbb{R}^2, t > 0 \right\}, \quad W_2 = \left\{ x + \frac{1}{2} i + t j \mid (x, t) \in \mathbb{R}^2, t > 0 \right\}, \]

and \( W_3 = U^{-1} W_2, \) where we use the same notation as in §3. We define \( \mathcal{HS} \) as the intersection of \( W_1 \cup W_2 \cup W_3 \) with \( \Delta \cup U^{-1} \Delta \). The aim of this section is to prove that \( \mathcal{HS} \) can be regarded as an immersed totally geodesic twice punctured torus in \( \text{BRC} \) and that it is conformally equivalent to the twice punctured torus \( \mathbb{T}_e \) studied in §2.
Lemma 4.1. The quadrilateral intersection of the plane of the lower faces of them is depicted in Figure 10. Using the diagrams in Figure rings complement is obtained from any two adjacent octahedra. The gluing pattern $U$

Using Figure 10 and the two right diagrams of Figure 9, we know both $\phi^\pm (r = 1\text{ to } 8)$ stands for the intersection of $W_1$ with a face with $\phi^\pm_r$.

Consider four aligning hyperbolic regular ideal octahedra $U^{-2}\Delta$, $U^{-1}\Delta$, $U$, and $U\Delta$. As we noted in Remark 3.1, they have a gluing pattern by which a Borromean rings complement is obtained from any two adjacent octahedra. The gluing pattern of the lower faces of them is depicted in Figure 10. Using the diagrams in Figure 9, we can get the gluing pattern of the upper faces.

We now consider the intersection of $W_1$ with $U^{-2}\Delta \cup U^{-1}\Delta \cup \Delta \cup U\Delta$. The edge with $r^\pm (r = 1 \text{ to } 8)$ stands for the intersection of the plane $W_1$ ($W_2$ or $W_3$) with a face with label $\phi^\pm_r$ ($r = 1 \text{ to } 8$).

**Lemma 4.1.** The quadrilateral $W_1 \cap U\Delta$ is identified with $W_3 \cap U^{-1}\Delta$.

**Proof.** Using Figure 10 and the two right diagrams of Figure 9, we know both $W_1 \cap U\Delta$ and $W_3 \cap U^{-1}\Delta$ are a quadrilateral composed by edges with $1^+, 6^+, 7^+$, and $4^-$. These edges are identified by the mapping $P_2$ defined in Proposition 3.2. \qed

**Lemma 4.2.** The quadrilateral $W_1 \cap U^{-2}\Delta$ is identified with $W_2 \cap \Delta$.

**Proof.** Using Figure 10 and the two left diagrams of Figure 9, we know both $W_1 \cap U^{-2}\Delta$ and $W_2 \cap \Delta$ are a quadrilateral composed by edges with $3^-, 1^-, 5^-$, and $7^-$. These edges are identified by $P_3$ of Proposition 3.2. \qed

Hence, in order to prove that $\mathcal{H}S$ is a twice punctured torus, we have only to show that $W_1 \cap (U^{-2}\Delta \cup U^{-1}\Delta \cup \Delta \cup U\Delta)$ is a twice punctured torus.

Since the model of the Borromean rings complement $\text{BRC}$ is obtained by gluing faces with $\phi_1^+$ and $\phi^-_1$, the edge with $7^-$ in $W_1 \cap U^{-1}\Delta$ (the left edge with $7^-$ in

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{Gluing pattern of the lower faces of $U^1\Delta$, $l = -3 \text{ to } 2$}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure11.png}
\caption{Labeling of the intersection of $W_1$ with $U^{-2}\Delta \cup U^{-1}\Delta \cup \Delta \cup U\Delta$. The edge with $r^\pm (r = 1 \text{ to } 8)$ stands for the intersection of $W_1$ with a face with $\phi^\pm_r$.}
\end{figure}
Figure 12. Gluing pattern for the twice punctured torus

Figure 11) and the one with $7^+$ in $W_1 \cap U^2 \Delta$ (the right edge with $7^+$ in Figure 11) must be identified. We then get a diagram in Figure 12. This gives a gluing pattern: the upper side and the lower side, the left side and the right side of the biggest square in Figure 12 are glued together. We thus have a torus. Since $(1 - 3i)/2, (1 - i)/2, (1 + i)/2, (1 + 3i)/2$, and $\infty$ are ideal vertices, a point obtained by identifying the first four vertices is a cusp of the torus and the center of the square ($\infty$) is another cusp. Hence, we have proved that $W_1 \cap (U^{-2}\Delta \cup U^{-1}\Delta \cup \Delta \cup U\Delta)$ is a twice punctured torus.

We now determine the mappings giving the gluing of the sides of $W_1 \cap (U^{-2}\Delta \cup U^{-1}\Delta \cup \Delta \cup U\Delta)$. We define three matrices $\tilde{P}, \tilde{Q},$ and $\tilde{R}$ as follows:

$$\tilde{P} = P_0^{-1}P_1P_{\infty} = \begin{pmatrix} i & 2 \\ 2i & 4 - i \end{pmatrix}, \quad \tilde{Q} = P_5^{-1} = \begin{pmatrix} 2 - i & 2i \\ -2i & 2 + i \end{pmatrix},$$

$$\tilde{R} = P_1P_{\infty}^{-1}P_1P_{\infty} = \begin{pmatrix} 1 + 2i & 2 - 2i \\ 4i & 5 - 2i \end{pmatrix}.$$

Lemma 4.3. The plane $W_1$ is invariant under the actions of $\tilde{P}, \tilde{Q},$ and $\tilde{R}$.

Proof. This is verified by direct calculation. □

The action of $\tilde{Q}^{-1}$ maps the semicircle with labels $8^-$ and $1^+$ to the one with $8^+$ and $1^-$ in Figure 11. Indeed, $\tilde{Q}^{-1}$ sends $(1 + i)/2$ to $(1 - i)/2$ and $(1 + 3i)/2$ to $(1 - 3i)/2$. Next, we take

$$\tilde{Q}^{-1}\tilde{R}^{-1}\tilde{P} = \begin{pmatrix} -1 & 4i \\ 0 & -1 \end{pmatrix}.$$

This is a translation on $W_1$ and glues the edge with $7^-$ in $W_1 \cap U^{-1}\Delta$ to the one with $7^+$ in $W_1 \cap U^2\Delta$. Finally, since $\tilde{P}$ sends $(1 + 3i)/2$ to $(1 + i)/2$ and $(1 + 5i)/2$ to $(1 - i)/2$, it maps the semicircle with $6^+$ and $3^-$ to the one with $6^-$ and $3^+$. We thus get the desired mappings.

Next, we conjugate actions on $W_1$ to those on the upper half plane. By the definition of $W_1$, we require a translation by $-1/2$ and a rotation by $\pi/2$:

$$V_t = \begin{pmatrix} 1 & -1/2 \\ 0 & 1 \end{pmatrix} \quad \text{and} \quad V_r = \begin{pmatrix} 1 + i & 0 \\ 0 & (1 - i)/2 \end{pmatrix}.$$
Define $V$ as $V_r V_l$:

\[
V = V_r V_l = \begin{pmatrix}
1 + i & -(1 + i)/2 \\
0 & (1 - i)/2
\end{pmatrix},
\]

We then get

\[
P = V \tilde{P} V^{-1} = \begin{pmatrix}
0 & -1 \\
1 & 4
\end{pmatrix}, \quad Q = V \tilde{Q} V^{-1} = \begin{pmatrix}
2 & -3 \\
-1 & 2
\end{pmatrix},
\]
\[
R = V \tilde{R} V^{-1} = \begin{pmatrix}
1 & 2 \\
2 & 5
\end{pmatrix}.
\]

All these are matrices used in §2. Let us define the group $\tilde{\Gamma}_t$ generated by $\tilde{P}$, $\tilde{Q}$, and $\tilde{R}$. The group $\tilde{\Gamma}_t$ is conjugate to $\Gamma_t$, that is, the twice punctured torus $T_t$ is mapped to the quotient space $\tilde{\mathbb{T}}_t = W_1/\tilde{\Gamma}_t$. We have already seen that in the model of the Borromean rings complement $\text{BRC}$, $\tilde{T}_t$ is identified with $\text{HS}$. Thus, there is an immersion of $\tilde{T}_t$ into the model of the Borromean rings complement $\text{BRC}$. We deduce a conclusion from the discussion:

**Theorem 4.4.** The plane $\text{HS}$ is an immersed totally geodesic twice punctured torus which is conformally equivalent to $T_t$.

Conjugating inversely the action of $A$ and $B$ on $H^2$ to $W_1$, we get

\[
\bar{A} = V^{-1} A V = \frac{1}{\sqrt{2}} \begin{pmatrix}
5 - i & -3 - 3i \\
-2i & -1 + i
\end{pmatrix},
\]
\[
\bar{B} = V^{-1} B V = \frac{1}{\sqrt{2}} \begin{pmatrix}
1 + i & 1 - i \\
2i & 3 - i
\end{pmatrix}.
\]

The plane $W_1$ is invariant under these actions. Let $\tilde{\Gamma}_o$ be a group generated by $\bar{A}$ and $\bar{B}$. Then the quotient space $\tilde{\mathbb{T}}_o = W_1/\tilde{\Gamma}_o$ can be regarded as an immersed totally geodesic once punctured torus in the Borromean rings complement $\text{BRC}$.

### 5. Vulakh-Schmidt tree

#### 5.1. Tree of quadruples of integers

In order to investigate the discrete part of the Markoff spectrum for the imaginary quadratic number field $\mathbb{Q}(i)$, L.Ya.Vulakh introduced the system of equations (1.2), which is an analogue of Markoff’s equation. Let $(x_1, x_2; y_1, y_2)$ denote a solution of (1.2) such that

\[(x_1, x_2, y_1, y_2) \in \mathbb{Z}^4, \quad 1 \leq x_1 \leq x_2, \quad 1 \leq y_1 \leq y_2.
\]

We call such a solution **Vulakh-Schmidt quadruple** (or, briefly, **VS quadruple**) after the works of L.Ya.Vulakh [37] and A.Schmidt [31].

We can simply verify that $(1, 1; 1, 1)$ is the unique solution satisfying $x_1 = x_2$ or $y_1 = y_2$. Setting $x_1 = 1$ and $y_1 = 1$, we get $(1, 5; 1, 3)$ which is the unique solution derived from $(1, 1; 1, 1)$. Suppose that $q = (\bar{x}_1, \bar{x}_2; \bar{y}_1, \bar{y}_2)$ is a VS quadruple different from $(1, 1; 1, 1)$. Then, setting $(x_1, y_1) = (\bar{x}_1, \bar{y}_1)$, $(\bar{x}_2, y_1)$, and $(\bar{x}_2, \bar{y}_2)$ in (1.2), we get from $q$ four quadratic equations. Solving them, four other quadruples are obtained. Since one of those derived from $q$ is the quadruple from which $q$ itself is obtained, three of them are new. Hence, a VS quadruple different from $(1, 1; 1, 1)$ always has three children which are explicitly written. Indeed, an infinite ternary tree the nodes of which are VS quadruples is built in the following way: the root of the tree is $(1, 5; 1, 3)$ and, a node $(x_1, x_2; y_1, y_2)$ being given, its three children are...
Figure 13. Labeling of the Vulakh-Schmidt tree

Table 2. VS quadruples

<table>
<thead>
<tr>
<th>label</th>
<th>VS quadruple</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\emptyset$</td>
<td>(1, 5; 1, 3)</td>
</tr>
<tr>
<td>$a$</td>
<td>(1, 65; 3, 11)</td>
</tr>
<tr>
<td>$b$</td>
<td>(5, 349; 3, 59)</td>
</tr>
<tr>
<td>$c$</td>
<td>(5, 29; 1, 17)</td>
</tr>
<tr>
<td>$aa$</td>
<td>(1, 901; 11, 41)</td>
</tr>
<tr>
<td>$ab$</td>
<td>(65, 62789; 11, 2857)</td>
</tr>
<tr>
<td>$ac$</td>
<td>(65, 4549; 3, 769)</td>
</tr>
<tr>
<td>$ba$</td>
<td>(5, 138881; 59, 1177)</td>
</tr>
<tr>
<td>$bb$</td>
<td>(349, 9718249; 59, 82361)</td>
</tr>
<tr>
<td>$bc$</td>
<td>(349, 24425; 3, 4129)</td>
</tr>
<tr>
<td>$ca$</td>
<td>(5, 11521; 17, 339)</td>
</tr>
<tr>
<td>$cb$</td>
<td>(29, 66985; 17, 1971)</td>
</tr>
<tr>
<td>$cc$</td>
<td>(29, 169; 1, 99)</td>
</tr>
</tbody>
</table>

$(x_1, 2y_2(4x_1y_2 - y_1) - x_1; y_2, 4x_1y_2 - y_1)$ for its left child,
$(x_2, 2y_2(4x_2y_2 - y_1) - x_2; y_2, 4x_2y_2 - y_1)$ for its center child,
$(x_2, 2y_1(4x_2y_1 - y_2) - x_2; y_1, 4x_2y_1 - y_2)$ for its right child.

(See §5.2 in [31].) We call this the Vulakh-Schmidt tree (or, briefly, VS tree).

In order to illustrate the VS tree, we define labels for its nodes. We label the root $\emptyset$. Its left child is labeled by $a$, its center child by $b$ and its right child by $c$. If a node has $L$ as a label, we label its left child $La$, its center child $Lb$ and its right child $Lc$. (See Figure 13.) In the following, we frequently use the expression “the node $L$” instead of “the node with a label $L$”. Table 2 gives correspondence between nodes of VS quadruples and labels with length less than 2. The beginning of the Vulakh-Schmidt tree can be built by Figure 13 and Table 2.

Let $\mathcal{N}(\Lambda)$ denote the set of members $x_1$ and $x_2$ in Vulakh-Schmidt quadruples, and $\mathcal{N}(M)$ the set of members $y_1$ and $y_2$:

$$\mathcal{N}(\Lambda) = \{\Lambda\} = \{1, 5, 29, 65, 169, 349, 901, 985, 4549, 5741, \cdots\},$$
$$\mathcal{N}(M) = \{m\} = \{1, 3, 11, 17, 41, 59, 99, 153, 339, 571, 577, \cdots\}.$$  

The set $\mathcal{N}(\Lambda)$ is used to represent the discrete part (1.3) of the Markoff spectrum for $\mathbb{Q}(i)$ (see [37] and [31]).

Remark 5.1. We use the prime $'$ to represent a relationship between a parent and its child in the VS tree, that is, $(x'_1, x'_2; y'_1, y'_2)$ denotes a child of $(x_1, x_2; y_1, y_2)$. The quadruple $(x'_1, x'_2; y'_1, y'_2)$ is uniquely determined if we know which child it is.
For example, if \((x_1', x_2', y_1', y_2')\) is the left child of \((x_1, x_2; y_1, y_2)\), then \((x_1', x_2'; y_1', y_2') = (x_1, 2y_2(4x_1y_2 - y_1) - x_1; y_2, 4x_1y_2 - y_1)\).

5.2. Tree of quadruples of matrices. We now propose an algorithm building a ternary tree the nodes of which are quadruples of matrices. The matrices are the following special ones corresponding to the elements of \(\mathcal{N}(\Lambda)\) and \(\mathcal{N}(M)\). We use in the definition (also in the sequel) two notations: for any matrix \(N = \begin{pmatrix} a & b \\ c & d \end{pmatrix}\), \(\kappa(N)\) denotes the \((2, 1)\)-entry of \(N\), namely, \(\kappa(N) = c; \mathbb{Z}/\sqrt{2}\) stands for the set of numbers of the form \(u/\sqrt{2}\) with \(u \in \mathbb{Z}\).

**Definition 5.2.** (i) For each \(\lambda \in \mathcal{N}(\Lambda)\), if a matrix \(\Lambda_\lambda\) belongs to \(\mathrm{SL}(2, \mathbb{Z})\), and satisfies \(\kappa(\Lambda_\lambda) = \lambda\) and \(\mathrm{tr}(\Lambda_\lambda) = 4\lambda\), then we call it a \(\Lambda\)-matrix associated with \(\lambda\).

(ii) For each \(m \in \mathcal{N}(M)\), if a matrix \(M_m\) belongs to \(\mathrm{SL}(2, \mathbb{Z}/\sqrt{2})\), and satisfies \(\kappa(M_m) = m/\sqrt{2}\) and \(\mathrm{tr}(M_m) = 2\sqrt{2} \cdot m\), then we call it a \(M\)-matrix associated with \(m\).

A quadruple of matrices is written in the form \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\), where the quadruple of the subscripts \((x_1, x_2; y_1, y_2)\) is a VS quadruple. Corresponding to the root of the VS tree \((1, 5; 1, 3)\), we define a quadruple of matrices of the root by \((\Lambda_1, \Lambda_5; M_1, M_3)\), where

\[
\begin{align*}
\Lambda_1 &= Q^{-1} = BA = \begin{pmatrix} 2 & 3 \\ 1 & 2 \end{pmatrix}, \quad M_1 = B = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 3 & 1 \end{pmatrix}, \\
\Lambda_5 &= M_3M_1 = \Lambda_1M_1^2 = \begin{pmatrix} 8 & 19 \\ 5 & 12 \end{pmatrix}, \quad M_3 = \Lambda_1M_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 5 & 11 \\ 3 & 7 \end{pmatrix}.
\end{align*}
\]

Note that \(A, B,\) and \(Q\) are matrices used in §2 and that \(\Lambda_1\) and \(\Lambda_5\) are \(\Lambda\)-matrices associated with 1 and 5; \(M_1\) and \(M_3\) are \(M\)-matrices associated with 1 and 3.

Any node of the tree is either of type \(I\) or of type \(II\). The root is assumed to be of type \(I\). The children of a node \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\) are defined in the following way.

**Algorithm VS.** (See Figure 14.)

- If \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\) is of type \(I\), then
  - its left child is \((\Lambda_{x_1}, \Lambda_{x_1}, M_{y_2}; M_{y_2}, \Lambda_{x_2}, \Lambda_{y_2})\) and is of type \(I\);
  - its center child is \((\Lambda_{x_2}, M_{y_2}^2, \Lambda_{x_1}; M_{y_2}, \Lambda_{y_2}, \Lambda_{x_2})\) and is of type \(II\);
  - its right child is \((\Lambda_{x_2}, \Lambda_{x_2}, M_{y_2}; M_{y_1}, \Lambda_{y_2}, M_{y_2})\) and is of type \(I\).

- If \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\) is of type \(II\), then
  - its left child is \((\Lambda_{x_1}, M_{y_1}^2, \Lambda_{x_1}; M_{y_2}, \Lambda_{y_2}, \Lambda_{x_1})\) and is of type \(II\);
  - its center child is \((\Lambda_{x_2}, \Lambda_{x_2}, M_{y_2}; M_{y_2}, \Lambda_{x_2}, \Lambda_{y_2})\) and is of type \(I\);
  - its right child is \((\Lambda_{x_2}, M_{y_1}^2, \Lambda_{x_2}; M_{y_1}, M_{y_2}, \Lambda_{x_2})\) and is of type \(II\).

We call the tree built by this algorithm, starting with the matrices of (5.1), the Vulakh-Schmidt matrix tree (or, briefly, VS matrix tree). The beginning of the Vulakh-Schmidt matrix tree can be built by Figure 13 and Table 3. We show in Table 4 some \(\Lambda\) and \(M\)-matrices in the VS matrix tree.

**Remark 5.3.** We write by \(|L|_b\) the number of occurrences of the letter \(b\) in a label \(L\). It is easily verified that the node \(L\) is of type \(I\) if and only if \(|L|_b\) is even; the node \(L\) is of type \(II\) if and only if \(|L|_b\) is odd.
\[(\Lambda_{x_1}, \Lambda_{x_2} ; \ M_{y_1}, M_{y_2}), I\]

\[(\Lambda_{x_1}, \Lambda_{x_1} M_{y_1}^2 ; \ M_{y_2}, \Lambda_{x_1} M_{y_2}), I\]

\[(\Lambda_{x_2}, \Lambda_{x_2} M_{y_1}^2 ; \ M_{y_2}, \Lambda_{x_2} M_{y_2}), I\]

\[(\Lambda_{x_1}, \Lambda_{x_2} ; \ M_{y_2}, \Lambda_{x_2} M_{y_1}), II\]

\[(\Lambda_{x_1}, \Lambda_{x_2} ; \ M_{y_2}, \Lambda_{x_2} M_{y_1}), II\]

\[(\Lambda_{x_1}, \Lambda_{x_2} ; \ M_{y_2}, \Lambda_{x_2} M_{y_1}), I\]

\[(\Lambda_{x_2}, \Lambda_{x_2} ; \ M_{y_2}, \Lambda_{x_2} M_{y_1}), I\]

\[(\Lambda_{x_1}, \Lambda_{x_2} ; \ M_{y_2}, \Lambda_{x_2} M_{y_1}), II\]

\[(\Lambda_{x_2}, \Lambda_{x_2} ; \ M_{y_2}, \Lambda_{x_2} M_{y_1}), II\]

\[(\Lambda_{x_1}, \Lambda_{x_2} ; \ M_{y_2}, \Lambda_{x_2} M_{y_1}), I\]

Figure 14. Illustration of Algorithm VS. The first is the case in which the parent is of type I. The second is the case in which the parent is of type II.

Table 3. Quadruples of matrices

<table>
<thead>
<tr>
<th>label</th>
<th>quadruple of matrices</th>
<th>type</th>
</tr>
</thead>
<tbody>
<tr>
<td>∅</td>
<td>(Λ_1, Λ_5 = M_{41} M_{29}; M_{1}, M_{3} = Λ_{1} M_{1})</td>
<td>I</td>
</tr>
<tr>
<td>a</td>
<td>(Λ_1, Λ_{60} = M_{11} M_{31}; M_{3}, M_{11} = Λ_{1} M_{3})</td>
<td>I</td>
</tr>
<tr>
<td>b</td>
<td>(Λ_5, Λ_{49} = M_{3} M_{59}; M_{3}, M_{59} = M_{3} M_{5})</td>
<td>II</td>
</tr>
<tr>
<td>c</td>
<td>(Λ_5, Λ_{29} = M_{17} M_{11}; M_{1}, M_{17} = Λ_{5} M_{1})</td>
<td>I</td>
</tr>
<tr>
<td>aa</td>
<td>(Λ_1, Λ_{901} = M_{41} M_{11}; M_{11}, M_{41} = Λ_{1} M_{11})</td>
<td>I</td>
</tr>
<tr>
<td>ab</td>
<td>(Λ_{65}, Λ_{62} = M_{11} M_{28}; M_{11}, M_{28} = M_{11} A_{65})</td>
<td>II</td>
</tr>
<tr>
<td>ac</td>
<td>(Λ_{65}, Λ_{45} = M_{76} M_{33}; M_{3}, M_{76} = Λ_{65} M_{33})</td>
<td>I</td>
</tr>
<tr>
<td>ba</td>
<td>(Λ_{5}, Λ_{13} = M_{59} M_{3}; M_{59}, M_{137} = M_{59} A_{5})</td>
<td>II</td>
</tr>
<tr>
<td>bb</td>
<td>(Λ_{349}, Λ_{97} = M_{23} M_{53}; M_{23}, M_{53} = Λ_{349} M_{53})</td>
<td>I</td>
</tr>
<tr>
<td>bc</td>
<td>(Λ_{349}, Λ_{24} = M_{42} M_{11}; M_{42}, M_{11} = Λ_{349} M_{11})</td>
<td>II</td>
</tr>
<tr>
<td>ca</td>
<td>(Λ_{5}, Λ_{11} = M_{339} M_{17}; M_{17}, M_{339} = Λ_{5} M_{17})</td>
<td>I</td>
</tr>
<tr>
<td>cb</td>
<td>(Λ_{29}, Λ_{60} = M_{17} M_{197}; M_{17}, M_{197} = M_{17} Λ_{29})</td>
<td>II</td>
</tr>
<tr>
<td>cc</td>
<td>(Λ_{29}, Λ_{169} = M_{60} M_{11}; M_{1}, M_{69} = Λ_{29} M_{1})</td>
<td>I</td>
</tr>
</tbody>
</table>

Remark 5.4. We also use the prime ’ to represent a relationship between a parent and its child in the VS matrix tree, that is, \((\Lambda_{x_1}, \Lambda_{x_2} ; M_{y_1}, M_{y_2})\) denotes a child of \((\Lambda_{x_1}, \Lambda_{x_2} ; M_{y_1}, M_{y_2})\). The quadruples of matrices are uniquely determined if we know the type of the parent and which child it is. For example, if it is the left child of \((\Lambda_{x_1}, \Lambda_{x_2} ; M_{y_1}, M_{y_2})\) of type I, then \((\Lambda_{x_1}, \Lambda_{x_2} ; M_{y_1}, M_{y_2}) = (\Lambda_{x_1}, \Lambda_{x_2}, M_{y_2}^2 ; M_{y_2}, M_{y_2})\).

With this notation, we can write Algorithm VS more simply. If a child \((\Lambda_{x_1}, \Lambda_{x_2} ; M_{y_1}, M_{y_2})\) is defined as type I, then \(M_{y_2} = \Lambda_{x_1} M_{y_1}^2\) and \(M_{y_2} = M_{y_2} M_{y_1}\); if it is defined as type II, then \(M_{y_2} = M_{y_2} M_{y_1}\) and \(M_{y_2} = \Lambda_{x_2} M_{y_2}\).

Definition 5.5. Let \((x_1, x_2; y_1, y_2)\) be a Vulakh-Schmidt quadruple. If both \(\Lambda_{x_1}\) and \(\Lambda_{x_2}\) are \(M\)-matrices associated with \(x_1\) and \(x_2\), and both \(M_{y_1}\) and \(M_{y_2}\) are \(M\)-matrices associated with \(y_1\) and \(y_2\), then we say that \((\Lambda_{x_1}, \Lambda_{x_2} ; M_{y_1}, M_{y_2})\) is associated with \((x_1, x_2; y_1, y_2)\).
Table 4. Examples of $\Lambda$-matrix and $M$-matrix

<table>
<thead>
<tr>
<th>label</th>
<th>the second matrix</th>
<th>the forth matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\emptyset$</td>
<td>$\Lambda_5 = \begin{pmatrix} 8 &amp; 19 \ 5 &amp; 12 \end{pmatrix}$</td>
<td>$M_3 = \frac{1}{\sqrt{2}} \begin{pmatrix} 5 &amp; 11 \ 3 &amp; 7 \end{pmatrix}$</td>
</tr>
<tr>
<td>$a$</td>
<td>$\Lambda_{65} = \begin{pmatrix} 112 &amp; 255 \ 65 &amp; 148 \end{pmatrix}$</td>
<td>$M_{11} = \frac{1}{\sqrt{2}} \begin{pmatrix} 19 &amp; 43 \ 11 &amp; 25 \end{pmatrix}$</td>
</tr>
<tr>
<td>$b$</td>
<td>$\Lambda_{349} = \begin{pmatrix} 562 &amp; 1343 \ 349 &amp; 834 \end{pmatrix}$</td>
<td>$M_{59} = \frac{1}{\sqrt{2}} \begin{pmatrix} 95 &amp; 227 \ 59 &amp; 141 \end{pmatrix}$</td>
</tr>
<tr>
<td>$c$</td>
<td>$\Lambda_{29} = \begin{pmatrix} 46 &amp; 111 \ 29 &amp; 70 \end{pmatrix}$</td>
<td>$M_{17} = \frac{1}{\sqrt{2}} \begin{pmatrix} 27 &amp; 65 \ 17 &amp; 41 \end{pmatrix}$</td>
</tr>
</tbody>
</table>

We have to verify that the VS matrix tree and the quadruples of matrices in the nodes are well-defined. With the notation in Remarks 5.1 and 5.4, a theorem to be proved is written in the following way:

**Theorem 5.6.** If a node $(\Lambda x_1, \Lambda x_2; M_{y_1}, M_{y_2})$ in the VS matrix tree is associated with a VS quadruple $(x_1, x_2; y_1, y_2)$, then each child $(\Lambda x'_1, \Lambda x'_2; M'_{y'_1}, M'_{y'_2})$ defined by Algorithm VS is associated with $(x'_1, x'_2; y'_1, y'_2)$.

Note that $(\Lambda x'_1, \Lambda x'_2; M'_{y'_1}, M'_{y'_2})$ has six possibilities by two types and three children. This will be proved in §7. The theorem ensures that the VS tree and the VS matrix tree correspond to each other in a natural way. We now have

**Corollary 5.7.** For each $\lambda \in \mathcal{N}(\Lambda)$, the matrix $\Lambda_\lambda$ in the VS matrix tree is associated with $\lambda$. For each $m \in \mathcal{N}(M)$, the matrix $M_m$ in the VS matrix tree is associated with $m$.

We deduce the following proposition from Definition 5.2 and the construction of the VS matrix tree.

**Proposition 5.8.** All $\Lambda$-matrices and $M$-matrices in the VS matrix tree are hyperbolic and are represented as words on the alphabet $\{A, B\}$, where $A$ and $B$ are the matrices in (2.4).

Theorem 5.6 is proved by inductive method (see §7). We can directly check that $(\Lambda_1, \Lambda_5; M_1, M_3)$, $(\Lambda_1, \Lambda_{65}; M_3, M_{11})$, $(\Lambda_5, \Lambda_{349}; M_3, M_{59})$, and $(\Lambda_5, \Lambda_{29}; M_1, M_{17})$ are associated with $(1, 5; 1, 3)$, $(1, 65; 3, 11)$, $(5, 349; 3, 59)$, and $(5, 29; 1, 17)$, respectively (see Table 4). Assuming that $(\Lambda x_1, \Lambda x_2; M_{y_1}, M_{y_2})$ is associated with $(x_1, x_2; y_1, y_2)$, we prove that, in each child, $(\Lambda x'_1, \Lambda x'_2; M'_{y'_1}, M'_{y'_2})$ defined by Algorithm VS is associated with $(x'_1, x'_2; y'_1, y'_2)$.

**Remark 5.9.** Note that $\Lambda$-matrix associated with $\lambda \in \mathcal{N}(\Lambda)$ and $M$-matrix associated with $m \in \mathcal{N}(M)$ are not unique. For example, we can construct another VS matrix tree by Algorithm VS starting with

$$\Lambda_1 = \begin{pmatrix} 4 & -1 \\ 1 & 0 \end{pmatrix}$$ \quad \text{and} \quad M_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 3 & 1 \\ 1 & 1 \end{pmatrix}.$$

Then we can prove that if a quadruple of matrices $(\Lambda x_1, \Lambda x_2; M_{y_1}, M_{y_2})$ in the tree is associated with a VS quadruple $(x_1, x_2; y_1, y_2)$, then its three children are also associated with the children of $(x_1, x_2; y_1, y_2)$. 
Fortunately, this ambiguity will not cause any trouble, because in the VS matrix tree built by Algorithm VS starting with (5.1), a matrix $\Lambda_\lambda$ for $\lambda \in \mathcal{N}(\Lambda)$ and a matrix $M_m$ for $m \in \mathcal{N}(M)$ are uniquely determined (see [2]).

5.3. Tree of quadruples of complex matrices. We introduce complex matrices which are analogues of $\Lambda$- and $M$-matrices in $\S 5.2$.

**Definition 5.10.**

(i) For each $\lambda \in \mathcal{N}(\Lambda)$, if a matrix $\tilde{\Lambda}_\lambda$ belongs to $\text{SL}(2, \mathbb{Z}[i])$, has the following form:

$$
\tilde{\Lambda}_\lambda = \begin{pmatrix} a + \lambda i & b + c i \\ 2\lambda i & d - \lambda i \end{pmatrix},
$$

and satisfies $\text{tr}(\tilde{\Lambda}_\lambda) = 4\lambda$, then we call it $\tilde{\Lambda}$-matrix associated with $\lambda$.

(ii) For each $m \in \mathcal{N}(M)$, if a matrix $\tilde{M}_m$ belongs to $\text{SL}(2, \mathbb{Z}[i]/\sqrt{2})$, has the following form:

$$
\tilde{M}_m = \frac{1}{\sqrt{2}} \begin{pmatrix} \alpha + mi & \beta + \gamma i \\ 2mi & \delta - mi \end{pmatrix},
$$

and satisfies $\text{tr}(\tilde{M}_m) = 2\sqrt{2} \cdot m$, then we call it $\tilde{M}$-matrix associated with $m$.

Here $\mathbb{Z}[i]/\sqrt{2}$ stands for the set of complex numbers of the form $u/\sqrt{2}$ with $u \in \mathbb{Z}[i]$; $a, b, c, d, \alpha, \beta, \gamma,$ and $\delta$ in the entries of the matrices are some integers.

The aim of this subsection is to construct a ternary tree the nodes of which are quadruples of complex matrices associated with the elements of $\mathcal{N}(\Lambda)$ and $\mathcal{N}(M)$. The tree is also defined inductively. A quadruple of complex matrices is written in the form $(\tilde{\Lambda}_{x_1}, \tilde{\Lambda}_{x_2}; \tilde{M}_{y_1}, \tilde{M}_{y_2})$, where the quadruple of the subscripts $(x_1, x_2; y_1, y_2)$ is a VS quadruple. Each node of the tree is either of type $I$ or of type $II$.

Corresponding to the root of the VS tree $(1, 5; 1, 3)$, we define a quadruple of complex matrices of the root by $(\tilde{\Lambda}_1, \tilde{\Lambda}_3 = \tilde{M}_3\tilde{M}_1; \tilde{M}_1, \tilde{M}_3 = \tilde{\Lambda}_1\tilde{M}_1)$, where $\tilde{\Lambda}_1$ and $\tilde{M}_1$ are the conjugate of $\Lambda_1$ and $M_1$ by $V$ (see (5.1) and (4.1)):

$$
\tilde{\Lambda}_1 = V^{-1}\Lambda_1 V = \begin{pmatrix} 2 + i & -2i \\ 2i & 2 - i \end{pmatrix},
\tilde{M}_1 = V^{-1}M_1 V = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 + i & 1 - i \\ 2i & 3 - i \end{pmatrix}.
$$

(5.4)

(Note that $\tilde{\Lambda}_1$ is used in [19].) The type of the root is assumed to be of type $I$. For a node $(\tilde{\Lambda}_{x_k}, \tilde{M}_{y_k}; \tilde{M}_{y_k})$, we define its children by Algorithm VS; to be precise, $\Lambda_{x_k}$ and $M_{y_k}$ ($k = 1, 2$) in the algorithm must be replaced by $\tilde{\Lambda}_{x_k}$ and $\tilde{M}_{y_k}$. The tree built in this way is called *Vulakh-Schmidt* (briefly, VS) complex matrix tree. Some $\tilde{\Lambda}$- and $\tilde{M}$-matrices in this tree are shown in Table 5, where we use the same labeling of the tree defined in $\S 5.2$.

Recall the Vulakh-Schmidt matrix tree, built in $\S 5.2$, the nodes of which are quadruples of real matrices associated with VS quadruples. Let $\Lambda_\lambda$ be a $\Lambda$-matrix associated with $\lambda \in \mathcal{N}(\Lambda)$ and let $M_m$ be a $M$-matrix associated with $m \in \mathcal{N}(M)$ in the VS matrix tree (see Corollary 5.7). We define $\Lambda_\lambda$ and $M_m$ as the conjugate of $\Lambda_\lambda$ and $M_m$ by $V$, namely,

$$
\tilde{\Lambda}_\lambda = V^{-1}\Lambda_\lambda V \quad \text{and} \quad \tilde{M}_m = V^{-1}M_m V.
$$

(5.5)

By construction, we get a proposition:
Table 5. Examples of $\tilde{\Lambda}$-matrix and $\tilde{M}$-matrix

<table>
<thead>
<tr>
<th>label</th>
<th>the second matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\emptyset$</td>
<td>$\tilde{\Lambda}_5 = \begin{pmatrix} 8 + 5i &amp; 2 - 12i \ 10i &amp; 12 - 5i \end{pmatrix}$</td>
</tr>
<tr>
<td>$a$</td>
<td>$\tilde{\Lambda}_{65} = \begin{pmatrix} 112 + 65i &amp; 18 - 160i \ 130i &amp; 148 - 65i \end{pmatrix}$</td>
</tr>
<tr>
<td>$b$</td>
<td>$\tilde{\Lambda}_{349} = \begin{pmatrix} 562 + 349i &amp; 136 - 846i \ 698i &amp; 834 - 349i \end{pmatrix}$</td>
</tr>
<tr>
<td>$c$</td>
<td>$\tilde{\Lambda}_{29} = \begin{pmatrix} 46 + 29i &amp; 12 - 70i \ 58i &amp; 70 - 29i \end{pmatrix}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>label</th>
<th>the forth matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\emptyset$</td>
<td>$\tilde{M}_3 = \frac{1}{\sqrt{2}} \begin{pmatrix} 5 + 3i &amp; 1 - 7i \ 6i &amp; 7 - 3i \end{pmatrix}$</td>
</tr>
<tr>
<td>$a$</td>
<td>$\tilde{M}_{11} = \frac{1}{\sqrt{2}} \begin{pmatrix} 19 + 11i &amp; 3 - 27i \ 22i &amp; 25 - 11i \end{pmatrix}$</td>
</tr>
<tr>
<td>$b$</td>
<td>$\tilde{M}_{59} = \frac{1}{\sqrt{2}} \begin{pmatrix} 95 + 59i &amp; 23 - 143i \ 118i &amp; 141 - 59i \end{pmatrix}$</td>
</tr>
<tr>
<td>$c$</td>
<td>$\tilde{M}_{17} = \frac{1}{\sqrt{2}} \begin{pmatrix} 27 + 17i &amp; 7 - 41i \ 34i &amp; 41 - 17i \end{pmatrix}$</td>
</tr>
</tbody>
</table>

**Proposition 5.11.** All matrices $\tilde{\Lambda}_\lambda$, $\lambda \in \mathcal{N}(\Lambda)$ and $\tilde{M}_m$, $m \in \mathcal{N}(M)$ in the VS complex matrix tree are equal to the matrices obtained by (5.5) from $\Lambda_\lambda$ and $M_m$ in the VS matrix tree.

The following theorem analogous to Corollary 5.7 is proved at the end of §7.

**Theorem 5.12.** For each $\lambda \in \mathcal{N}(\Lambda)$, the matrix $\tilde{\Lambda}_\lambda$ in the VS complex matrix tree is associated with $\lambda$. For each $m \in \mathcal{N}(M)$, the matrix $\tilde{M}_m$ in the VS complex matrix tree is associated with $m$.

Thanks to this theorem, each quadruple of matrices $(\tilde{\Lambda}_{x_1}, \tilde{\Lambda}_{x_2}; \tilde{M}_{y_1}, \tilde{M}_{y_2})$ in the VS complex matrix tree is associated with $(x_1, x_2; y_1, y_2)$ in the following sense:

**Definition 5.13.** Let $(x_1, x_2; y_1, y_2)$ be a VS quadruple. If both $\tilde{\Lambda}_{x_1}$ and $\tilde{\Lambda}_{x_2}$ are $\tilde{\Lambda}$-matrices associated with $x_1$ and $x_2$, and both $\tilde{M}_{y_1}$ and $\tilde{M}_{y_2}$ are $\tilde{M}$-matrices associated with $y_1$ and $y_2$, then we say that $(\tilde{\Lambda}_{x_1}, \tilde{\Lambda}_{x_2}; \tilde{M}_{y_1}, \tilde{M}_{y_2})$ is associated with $(x_1, x_2; y_1, y_2)$.

By virtue of (5.2), (5.3), and the construction of the VS complex matrix tree, we have a similar result to Proposition 5.8:

**Proposition 5.14.** All $\tilde{\Lambda}$-matrices and $\tilde{M}$-matrices in the VS complex matrix tree are hyperbolic and are represented as words on the alphabet $\{\tilde{A}, \tilde{B}\}$, where $\tilde{A}$ and $\tilde{B}$ are the matrices in (4.2).

**Remark 5.15.** Note that $\tilde{\Lambda}$-matrix associated with $\lambda \in \mathcal{N}(\Lambda)$ and $\tilde{M}$-matrix associated with $m \in \mathcal{N}(M)$ are not unique, but they are unique in the VS complex matrix tree built by Algorithm VS starting with (5.4) (see Remark 5.9).
6. Simple closed geodesics

Let us begin by recalling a basic fact on two generator free group. Let \( \langle g, h \rangle \) be a free group generated by \( g \) and \( h \). An element \( g' \) is called a generator of \( \langle g, h \rangle \) if there exists a \( h' \) such that \( g' \) and \( h' \) generate \( \langle g, h \rangle \). We then also say that \( g' \) is represented as a primitive word in the two generator free group \( \langle g, h \rangle \). It is well-known (see, for example, [25]) that the outer automorphism group of \( \langle g, h \rangle \) is generated by the following three operations: exchanging \( g \) and \( h \); replacing \( g \) by \( g^{-1} \); replacing \( g \) by \( gh \). Combining this fact with the definition of matrices in the VS matrix tree (Algorithm VS), we get

**Proposition 6.1.** Every \( \Lambda \)-matrix associated with \( \lambda \in \mathcal{N}(\Lambda) \) in the VS matrix tree is a generator of \( \Gamma_o \). Every \( M \)-matrix associated with \( m \in \mathcal{N}(M) \) in the VS matrix tree is also a generator of \( \Gamma_o \).

Any pair of \( \Lambda \)-matrices cannot generate \( \Gamma_o \), because the group generated by two \( \Lambda \)-matrices must be a subgroup of \( \text{SL}(2, \mathbb{Z}) \), but \( \Gamma_o \) cannot be included in \( \text{SL}(2, \mathbb{Z}) \). Contrasting with this fact, we can prove the following:

**Proposition 6.2.** Let \( (\Lambda_1, \Lambda_2; M_{g_1}, M_{g_2}) \) be the quadruple of matrices associated with a VS quadruple \( (x_1, x_2; y_1, y_2) \) in the VS matrix tree. Then \( M_{g_1} \) and \( M_{g_2} \) generate \( \Gamma_o \).

**Proof.** By Definition 5.2, we have \( \text{tr}(\Lambda_2) = 4x_2 \), \( \text{tr}(M_{g_1}) = 2\sqrt{2}y_1 \), and \( \text{tr}(M_{g_2}) = 2\sqrt{2}y_2 \). From Algorithm VS, \( \Lambda_2 \) is defined as \( M_{g_1} \) or \( M_{g_2}M_{g_1} \). Consider the triple \( (\text{tr}(M_{g_1}), \text{tr}(M_{g_2}), \text{tr}(M_{g_2}M_{g_1})) \). Since \( (x_1, x_2; y_1, y_2) \) satisfies (1.2), this triple satisfies Fricke’s equation. Hence, \( \Gamma_o = \langle M_{g_1}, M_{g_2} \rangle \) is proved. \( \Box \)

The following proposition is very useful (see [22]):

**Proposition 6.3** (Nielsen). Let \( \langle g, h \rangle \) be a group the quotient space of which is a once punctured torus. Then, a geodesic \( \tilde{\gamma} \) in \( \mathbb{H}^2 \) is the axis of a generator of \( \langle g, h \rangle \) if and only if \( \tilde{\gamma} \) projects to a simple closed geodesic on the once punctured torus \( \mathbb{H}^2/\langle g, h \rangle \).

Recall that the geodesic in \( \mathbb{H}^2 \) fixed by a hyperbolic element \( g \) is called the axis of \( g \) and that a simple geodesic is a geodesic having no self-intersections.

We now deduce a theorem from Propositions 6.1 and 6.3:

**Theorem 6.4.** The axes of each \( \Lambda \)-matrix associated with \( \lambda \in \mathcal{N}(\Lambda) \) and of each \( M \)-matrix associated with \( m \in \mathcal{N}(M) \) in the VS matrix tree project to simple closed geodesics on \( \mathbb{T}_o \).

Since the twice punctured torus \( \mathbb{T}_t \) is a 2-fold cover of \( \mathbb{T}_o \) (see §2), we immediately get a corollary:

**Corollary 6.5.** The axes in Theorem 6.4 also project to simple closed geodesics on \( \mathbb{T}_t \).

The Euclidean height of a geodesic \( \tilde{\gamma} \) in \( \mathbb{H}^2 \) is defined as \( |\eta - \xi|/2 \) if \( \eta \) and \( \xi \) are finite or \( \infty \) otherwise, where \( \eta \) and \( \xi \) are the two endpoints of \( \tilde{\gamma} \).

**Proposition 6.6.** The Euclidean height of the axis of \( \Lambda \)-matrix associated with \( \lambda \in \mathcal{N}(\Lambda) \) and that of the axis of \( M \)-matrix associated with \( m \in \mathcal{N}(M) \) are

\[
\sqrt{4 - \frac{1}{\lambda^2}} \quad \text{and} \quad \sqrt{4 - \frac{2}{m^2}}.
\]
Toally equivalent, this can be regarded as a tessellation of the other three equivalent possibilities (see [16]):

Proof. These are directly computed by Definition 5.2.

We here explain that the simple closed geodesics on $\mathbb{T}_a$ are essentially obtained from the axes of $\Lambda$- and $M$-matrices in the VS matrix tree.

The conformal mapping $\varphi_4$ between $\mathbb{T}_{(A_1, R_1)}$ and $\mathbb{C}/\langle 1, i \rangle$ mentioned in §2 gives the abelian image of $\mathbb{T}_{(P, Q, R)}$. Figure 15 depicts a tessellation of the complex plane $\mathbb{C}$ by the abelian images of $\mathbb{T}_{(P, Q, R)}$. Since $\mathbb{T}_t$ and $\mathbb{T}_{(P, Q, R)}$ are conformally equivalent, this can be regarded as a tessellation of $\mathbb{C}$ by the abelian images of $\mathbb{T}_r$. We take here $\{A, B\}$ corresponding to $\{i, 1\}$ (as ordered pair). There are the other three equivalent possibilities (see [16]): $\{A, B\}$ corresponding to $\{i, -1\}$, $\{1, i\}$, or $\{-1, i\}$.

Identify $\mathbb{C}$ with $\mathbb{R}^2$ in the standard way. Let $\Omega = \{(k, l) \in \mathbb{Z}^2\}$, namely, $\Omega$ is the set of the images of $(0, 0) \in \mathbb{R}^2$ by the action of the group $\langle 1, i \rangle$. The lattice $\Omega$ is decomposed into the following two disjoint sublattices, each of which corresponds to one of the two cusps of $\mathbb{T}_t$:

$$
\Omega_w = \{(k, l) \in \Omega \mid (k, l) \equiv (0, 0) \text{ or } (1, 1) \pmod{2}\},
$$

$$
\Omega_b = \{(k, l) \in \Omega \mid (k, l) \equiv (1, 0) \text{ or } (0, 1) \pmod{2}\}.
$$

The white points in Figure 15 stand for the elements of $\Omega_w$ and the black points stand for those of $\Omega_b$. (The origin, $(0, 0)$, is a white point.)

Recall that each matrix $N$ in the VS matrix tree is represented as a word on the alphabet $\{A, B\}$ (Proposition 5.8). We define the Euclidean pair (briefly, $E$-pair) of $N$ as $(|N|_B, |N|_A)$, where $|N|_B$ stands for the number of $B$ occurring in the word of $N$ and $|N|_A$ for the number of $A$.

Let $\Lambda_\lambda$ be a $\Lambda$-matrix associated with $\lambda \in \mathcal{N}(\Lambda)$ and $M_m$ be a $M$-matrix associated with $m \in \mathcal{N}(M)$ in the VS matrix tree. We write $(\lambda_1, \lambda_2)$ for the $E$-pair of $\Lambda_\lambda$, and $(m_1, m_2)$ for the $E$-pair of $M_m$. A quadruple of matrices induces a quadruple of $E$-pairs; for example, for the root $(\Lambda_1, \Lambda_\varphi; M_1, M_3)$ of the VS matrix tree, the quadruple of $E$-pairs is $\{(1, 1), (3, 1); (1, 0), (2, 1)\}$.

Let $((\lambda_1, \lambda_2), (\lambda_1', \lambda_2'; (m_1, m_2), (m_1', m_2'))$ be the quadruple of $E$-pairs for a quadruple of matrices $(\Lambda_1, \Lambda_\varphi; M_m, M_m')$ in the VS matrix tree. The following relations are deduced from Algorithm VS and the definition of $E$-pair:

$$(m_1', m_2') = (\lambda_1, \lambda_2) + (m_1, m_2),$$

$$(\lambda_1', \lambda_2') = (m_1, m_2) + (m_1', m_2') = (\lambda_1, \lambda_2) + 2(m_1, m_2).$$

Figure 15. Two colored lattice in the complex plane and representation of some $E$-pairs in it. The beginning point of the vectors is the origin $(0, 0)$. 

\[\begin{array}{c}
\begin{array}{cc}
\mathbb{T}_a & \mathbb{T}_b \\
\end{array}
\end{array}\]

\[\begin{array}{c}
\begin{array}{cc}
\Lambda_1 & M_1 \\
\end{array}
\end{array}\]

\[\begin{array}{c}
\begin{array}{cc}
\Lambda_5 & M_5 \\
\end{array}
\end{array}\]

\[\begin{array}{c}
\begin{array}{cc}
\text{Figure 15. Two colored lattice in the complex plane and representation of some E-pairs in it. The beginning point of the vectors is the origin (0, 0).}
\end{array}
\end{array}\]
Since the E-pair of $\Lambda$ is $(1, 1)$ and that of $M$ is $(1, 0)$, using these relations, we easily verify that the E-pair $(\lambda_1, \lambda_2)$ of any matrix $\Lambda$ satisfies $(\lambda_1, \lambda_2) \equiv (1, 1) \pmod{2}$ and the E-pair $(m_1, m_2)$ of any matrix $M$ satisfies $(m_1, m_2) \equiv (1, 0)$ or $(0, 1) \pmod{2}$ (see Figure 15).

Moreover, we can prove the following theorem (see [2]).

**Theorem 6.7.**  
(i) There exists a bijection between the set of the E-pair of $\Lambda$-matrices and the set $\Omega_k \cap \{(k, l) \mid (k, l) \text{ are mutually prime and } 0 < l \leq k\}$.

(ii) There exists a bijection between the set of the E-pair of $M$-matrices and the set $\Omega_b \cap \{(k, l) \mid (k, l) \text{ are mutually prime and } 0 \leq l < k\}$.

Considering the other three equivalent correspondences of $\{A, B\}$ to $\{i, -1\}$, $\{1, i\}$, and $\{-1, i\}$, the set of the mutually prime pairs in $\Omega$ is covered by the set in Theorem 6.7 and its equivalent sets. We thus have

**Corollary 6.8.** The set of the simple closed geodesics on the once punctured torus $T_o$ is decomposed into the two sets: a set of the projection of the axis of $\Lambda$-matrix and its equivalent and a set of the projection of the axis of $M$-matrix and its equivalent.

We showed in §4 the conjugate between the generators of the groups $\Gamma_o$ and $\tilde{\Gamma}_o$, and between those of $\Gamma_t$ and $\tilde{\Gamma}_t$. Hence, Propositions 6.1 and 6.2, and Theorem 6.4 are translated into the context of complex matrices.

**Proposition 6.9.** Every $\tilde{\Lambda}$-matrix associated with $\lambda \in \mathcal{N}(\Lambda)$ in the VS complex matrix tree is a generator of $\tilde{\Gamma}_o$. Every $\tilde{M}$-matrix associated with $m \in \mathcal{N}(M)$ in the VS complex matrix tree is also a generator of $\tilde{\Gamma}_o$.

**Proposition 6.10.** Let $\tilde{(\Lambda x_1, \Lambda x_2; M y_1, M y_2)}$ be the quadruple of matrices associated with a VS quadruple $(x_1, x_2; y_1, y_2)$ in the VS complex matrix tree. Then $\tilde{M y_1}$ and $\tilde{M y_2}$ generate $\tilde{\Gamma}_o$.

**Theorem 6.11.** The axes of each $\tilde{\Lambda}$-matrix associated with $\lambda \in \mathcal{N}(\Lambda)$ and of each $\tilde{M}$-matrix associated with $m \in \mathcal{N}(M)$ in the VS matrix tree project to simple closed geodesics on $\tilde{T}_o$.

**Corollary 6.12.** The axes in Theorem 6.11 also project to simple closed geodesics on $\tilde{T}_t$.

The Euclidean height of a geodesic $\tilde{\gamma}$ in $\mathbb{H}^3$ is defined in the same way as of a geodesic in $\mathbb{H}^2$: let $\eta$ and $\xi$ be the two endpoints of $\tilde{\gamma}$, then it is defined as $|\eta - \xi|/2$ if $\eta$ and $\xi$ are finite or $\infty$ otherwise.

**Proposition 6.13.** The Euclidean height of the axis of $\tilde{\Lambda}$-matrix associated with $\lambda \in \mathcal{N}(\Lambda)$ and that of the axis of $\tilde{M}$-matrix associated with $m \in \mathcal{N}(M)$ are

$$\frac{1}{2} \sqrt{4 - \frac{1}{\lambda^2}} \quad \text{and} \quad \frac{1}{2} \sqrt{4 - \frac{2}{m^2}}.$$  

Proof. These are directly checked by (5.2) and (5.3). \hfill \Box

Theorem 1.6 follows from Theorem 4.4, Corollary 6.12, and Proposition 6.13.

Let us discuss the maximality of the Euclidean height of the axis of $\tilde{\Lambda}$.

Two complex binary indefinite quadratic forms $f$ and $g$ are equivalent if either there exists a nonzero $\alpha \in \mathbb{C}$ with $g = \alpha f$ or there exists an element $L = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$
of $\text{SL}(2, \mathbb{Z}[i])$ such that $g(x, y) = (f \circ L)(x, y) = f(ax + by, cx + dy)$. It is easily checked that $\sqrt{|D(f)|}/m_1(f) = \sqrt{|D(g)|}/m_1(g)$ if $f$ and $g$ are equivalent.

Let $\gamma_f$ be a geodesic whose endpoints are the roots of the equation $f(x, 1) = 0$ for a complex binary quadratic form $f$. Define $H(\gamma_f) = \sup\{h_E(g(\gamma_f)) \mid g \in \text{SL}(2, \mathbb{Z}[i])\}$, where $h_E(\gamma)$ stands for the Euclidean height of a geodesic $\gamma$.

**Proposition 6.14.** $2H(\gamma_f) = \sqrt{|D(f)|}/m_1(f)$.

**Proof.** We take a complex binary quadratic form $f(x, y) = \alpha x^2 + \beta xy + \gamma y^2$. There is no loss of generality if we suppose $D(f) = 1$.

If $\alpha \neq 0$, computing the root of $f(x, 1) = 0$, we get $h_E(\gamma_f) = 1/(2|\alpha|)$.

Let $\{(x_i, y_i)\}$ be a sequence of points in $\mathbb{Z}[i]$ with $\lim_{i \to \infty} |f(x_i, y_i)| = m_1(f)$. Choose $A_i \in \text{SL}(2, \mathbb{Z}[i])$ with $A_i \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} x_i \\ y_i \end{pmatrix}$ and define $(f \circ A_i)(x, y) = g_i(x, y) = ax^2 + bx + cy^2 + d$. We then have

$$\lim_{i \to \infty} |f(x_i, y_i)| = \lim_{i \to \infty} |(f \circ A_i)(1, 0)| = \lim_{i \to \infty} |g_i(1, 0)| = \lim_{i \to \infty} |a_i| = \lim_{i \to \infty} \frac{1}{2h_E(\gamma_i)},$$

where $\gamma_i$ is a geodesic whose endpoints are the roots of $g_i(x, 1) = 0$. Since $H(\gamma_f) \geq h_E(\gamma) = 1/(2|\alpha|)$, we get $2H(\gamma_f) \geq 1/m_1(f)$.

If $2H(\gamma_f) > 1/m_1(f)$, then there exists a form $g(x, y) = ax^2 + bxy + cy^2$ with $D(g) = 1$ which is equivalent to $f$ and satisfies $2h_E(\gamma_g) > 1/m_1(f)$. Using $h_E(\gamma_g) = 1/(2|\alpha|)$, we get $1/(2|\alpha|) > 1/(2m_1(f))$. It follows that $m_1(g) = m_1(f) > |\alpha| = |g(1, 0)|$ contrary to the definition of $m_1(g)$. $2H(\gamma_f) = 1/m_1(f)$ has been proved.

If $\alpha = 0$, then the equation is obtained from $H(\gamma_f) = \infty$ and $m_1(f) = 0$. \(\square\)

For a matrix $\tilde{A}_\lambda$ in the complex VS matrix tree, associated with $\lambda \in \mathcal{N}(\Lambda)$, we define the form $f_{\tilde{A}_\lambda}$ by the fixed point equation of the action of $\tilde{A}_\lambda$. Let $\gamma_{f_{\tilde{A}_\lambda}}$ be a geodesic whose endpoints are its fixed points. It follows from Proposition 6.13 that $h_E(\gamma_{f_{\tilde{A}_\lambda}}) = (1/2)\sqrt{4 - (1/\lambda^2)}$. Its double is the value of the VS spectrum for $\lambda$.

Moreover, we can prove $m_1(f_{\tilde{A}_\lambda}) = f_{\tilde{A}_\lambda}(1, 0) = \lambda$. A proposition is deduced from these facts and Proposition 6.14:

**Proposition 6.15.** $H(\gamma_{f_{\tilde{A}_\lambda}})$ is attained by $h_E(\gamma_{f_{\tilde{A}_\lambda}})$ and $\sqrt{|D(f_{\tilde{A}_\lambda})|}/m_1(f_{\tilde{A}_\lambda}) = 2h_E(\gamma_{f_{\tilde{A}_\lambda}})$.

Theorem 1.7 follows from Corollary 6.8 and Proposition 6.15.

7. PROOFS

We prove in this section Theorems 5.6 and 5.12. Most of the section is a proof of the first theorem.

Let $(x_1, x_2; y_1, y_2)$ be a VS quadruple. Suppose that $(\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})$ is a quadruple of matrices associated with $(x_1, x_2; y_1, y_2)$. In this section we always describe these matrices in the following way:

$$\Lambda_{x_k} = \begin{pmatrix} a_k & b_k \\ x_k & d_k \end{pmatrix} \quad \text{and} \quad M_{y_k} = \frac{1}{\sqrt{2}} \begin{pmatrix} a_k & \beta_k \\ y_k & \delta_k \end{pmatrix} \quad \text{for} \quad k = 1, 2.$$

By Definition 5.2, $a_k, b_k, d_k, \alpha_k, \beta_k$, and $\delta_k$ are integers and satisfy

$$a_k + d_k = 4x_k, \quad a_kd_k - b_kx_k = 1, \quad \alpha_k + \delta_k = 4y_k, \quad \alpha_k\delta_k - \beta_ky_k = 2.$$
Let \((x'_1, x'_2; y'_1, y'_2)\) be a child of \((x_1, x_2; y_1, y_2)\) and let \((\Lambda_{x'_1}, \Lambda_{x'_2}; M_{y'_1}, M_{y'_2})\) be a quadruple of matrices defined by Algorithm VS from \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\). We give a very rough sketch of proofs: introducing some relations between a pair of matrices in \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\), we prove that \(M_{y'_2}\) is associated with \(y'_2\) and \(\Lambda_{x'_2}\) is associated with \(x'_2\) provided that pairs of matrices satisfy these relations; then we show pairs of matrices in \((\Lambda_{x'_1}, \Lambda_{x'_2}; M_{y'_1}, M_{y'_2})\) satisfy the relations.

7.1. \(\Lambda M\)-pair and \(M_{y'_2}\). Recall that \(M_{y'_2}\) is defined by \(\Lambda_{x'_2}; M_{y'_1}\) or \(M_{y'_1}; \Lambda_{x'_2}\) (see Remark 5.4), where both \(\Lambda_{x'_1}\) and \(M_{y'_1}\) are matrices inherited from the quadruple associated with \((x_1, x_2; y_1, y_2)\). To be precise, there are six ways of defining \(M_{y'_2}\). We introduce six relations corresponding to them.

**Definition 7.1.**

(i) If the entries of \(\Lambda_{x_1}, M_{y_1}\), and \(M_{y_2}\) satisfy \(a_1y_2 = x_1\alpha_2 + y_1\), then we say that \((\Lambda_{x_1}, M_{y_2})\) is a \(\Lambda M\)-pair of type \(I_\alpha\) in \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\).

(ii) If the entries of \(\Lambda_{x_2}, M_{y_1}\), and \(M_{y_2}\) satisfy \(d_2y_2 = x_2\delta_2 + y_1\), then we say that \((\Lambda_{x_2}, M_{y_2})\) is a \(\Lambda M\)-pair of type \(I_\delta\) in \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\).

(iii) If the entries of \(\Lambda_{x_2}, M_{y_1}\), and \(M_{y_2}\) satisfy

\[
\begin{align*}
  a_2y_1 &= x_2\alpha_1 + y_2, \\
  d_2y_2 &= x_2\delta_1 + y_2,
\end{align*}
\]

then we say that \((\Lambda_{x_2}, M_{y_1})\) is a \(\Lambda M\)-pair of type \(I_c\) in \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\).

(iv) If the entries of \(\Lambda_{x_1}, M_{y_1}\), and \(M_{y_2}\) satisfy \(s_1y_2 = x_1\beta_2 + y_1\), then we say that \((\Lambda_{x_1}, M_{y_2})\) is a \(\Lambda M\)-pair of type \(II_\beta\) in \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\).

(v) If the entries of \(\Lambda_{x_2}, M_{y_1}\), and \(M_{y_2}\) satisfy \(s_2y_2 = x_2\beta_1 + y_1\), then we say that \((\Lambda_{x_2}, M_{y_2})\) is a \(\Lambda M\)-pair of type \(II_\beta\) in \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\).

(vi) If the entries of \(\Lambda_{x_2}, M_{y_1}\), and \(M_{y_2}\) satisfy \(d_2y_1 = x_2\delta_1 + y_2\), then we say that \((\Lambda_{x_2}, M_{y_2})\) is a \(\Lambda M\)-pair of type \(II_c\) in \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\).

**Example 7.2.** Using (5.1) and Table 4, we can directly check that \((\Lambda_1, M_3)\) (resp. \((\Lambda_5, M_5)\), \((\Lambda_5, M_1)\)) is a \(\Lambda M\)-pair of type \(I_\alpha\) (resp. \(I_\delta, I_c\)) in \((\Lambda_1, \Lambda_3; M_1, M_3)\) and that \((\Lambda_5, M_5)\) (resp. \((\Lambda_{349}, M_{59}), (\Lambda_{349}, M_3)\)) is a \(\Lambda M\)-pair of type \(II_\beta\) (resp. \(II_c, II_\beta\)) in \((\Lambda_5, \Lambda_{349}; M_3, M_{59})\).

**Lemma 7.3.** Suppose that \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\) is associated with \((x_1, x_2; y_1, y_2)\).

(i) If \((\Lambda_{x_1}, M_{y_2})\) is a \(\Lambda M\)-pair of type \(I_\alpha\) (resp. of type \(II_\beta\)) in \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\), then \(\Lambda_{x_2}, M_{y_2}\) (resp. \(M_{y_2}, \Lambda_{x_2}\)) is a \(\Lambda\)-matrix associated with \(4x_1y_2 - y_1\).

(ii) If \((\Lambda_{x_2}, M_{y_2})\) is a \(\Lambda M\)-pair of type \(I_\delta\) (resp. of type \(II_\beta\)) in \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\), then \(M_{y_2}, \Lambda_{x_2}\) (resp. \(\Lambda_{x_2}, M_{y_2}\)) is a \(\Lambda\)-matrix associated with \(4x_2y_2 - y_1\).

(iii) If \((\Lambda_{x_2}, M_{y_1})\) is a \(\Lambda M\)-pair of type \(I_c\) (resp. of type \(II_c\)) in \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\), then \(\Lambda_{x_2}, M_{y_1}\) (resp. \(M_{y_1}, \Lambda_{x_2}\)) is a \(\Lambda\)-matrix associated with \(4x_2y_1 - y_2\).

Note that \(4x_1y_2 - y_1, 4x_2y_2 - y_1, \) and \(4x_2y_1 - y_2\) are equal to \(y'_2\) in the left, center, and right child of \((x_1, x_2; y_1, y_2)\), respectively.

**Proof.** These are proved by direct calculations. We here prove (iii) for the case that \((\Lambda_{x_2}, M_{y_1})\) is a \(\Lambda M\)-pair of type \(I_c\) in \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\).

Since

\[
\Lambda_{x_2} M_{y_1} = \frac{1}{\sqrt{2}} \begin{pmatrix}
  a_2\alpha_1 + b_2y_1 & a_2\beta_1 + b_2\delta_1 \\
  x_2\alpha_1 + d_2y_1 & x_2\beta_1 + d_2\delta_1
\end{pmatrix},
\]

we have to verify

\[
\begin{align*}
  x_2\alpha_1 + d_2y_1 &= 4x_2y_1 - y_2 \\
  \text{tr}(\Lambda_{x_2} M_{y_1}) &= \frac{1}{\sqrt{2}}(a_2\alpha_1 + b_2y_1 + x_2\beta_1 + d_2\delta_1) = 2\sqrt{2}(4x_2y_1 - y_2).
\end{align*}
\]
The first equation follows from (7.2) and \( \text{tr}(\Lambda_{x_2}) = a_2 + d_2 = 4x_2 \).
We modify some equations of (7.1) in the following forms:

\[
b_2 = \frac{a_2d_2 - 1}{x_2}, \quad \beta_1 = \frac{a_1\delta_1 - 2}{y_1}, \quad d_2 = 4x_2 - a_2, \quad \text{and} \quad \delta_1 = 4y_1 - a_1.
\]

Substituting these in the second term of the second equation, by (7.1), we get

\[
\text{tr}(\Lambda_{x_2}M_{y_2}) = \frac{1}{\sqrt{2}} \cdot \frac{1}{x_2y_1} \left( 2a_2\alpha_1x_2y_1 - (a_2^2 + 1)y_1^2 - (\alpha_1^2 + 2)x_2^2 + 16x_2^2y_1^2 \right).
\]

By virtue of (1.2) and (7.2), it is changed into

\[
\frac{1}{\sqrt{2}} \cdot \frac{1}{x_2y_1} (16x_2^2y_1^2 - 2x_2^2 - (y_1^2 + y_2^2)) = \frac{4}{\sqrt{2}} (4x_2y_1 - y_2).
\]

The other cases are proved in the same way. \( \square \)

### 7.2. **MM-pair and \( \Lambda_{x_2} \)**

Let \((x_1, x_2; y_1, y_2)\) be a VS quadruple. Suppose that \(\Lambda_{x_1}, M_{y_1}, \text{and } M_{y_2}\) are associated with \(x_1, y_1, \text{and } y_2\), respectively. We discuss a sufficient condition so that \((\Lambda_{x_2}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\) is associated with \((x_1, x_2; y_1, y_2)\).

Recall that in \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\) the matrix \(\Lambda_{x_2}\) is defined as either \(M_{y_1}M_{y_2} = M_{y_1}^2\Lambda_{x_1}\) or \(M_{y_2}M_{y_1} = M_{y_1}^2\Lambda_{x_1}^2\). We prove a lemma.

#### Lemma 7.4.

The matrix \(\Lambda_{x_2}\) is in the group \(\text{SL}(2, \mathbb{Z})\).

**Proof.** Using \(\beta_1y_1 = a_1\delta_1 - 2 \text{ and } a_1 + \delta_1 = 4y_1\), we get

\[
M_{y_2}^2 = \frac{1}{2} \left( \begin{array}{cc} \alpha_1^2 + \beta_1y_1 & \beta_1(\alpha_1 + \delta_1) \\ y_1(\alpha_1 + \delta_1) & \beta_1y_1 + \delta_1^2 \end{array} \right) = \left( \begin{array}{cc} 2y_1\alpha_1 - 1 & 2y_1\beta_1 \\ 2y_1^2 & 2y_1\delta_1 - 1 \end{array} \right).
\]

Hence, \(M_{y_2}^2\) is an element of \(\text{SL}(2, \mathbb{Z})\). Since \(\Lambda_{x_2}\) is defined as \(M_{y_1}^2\Lambda_{x_1}\) or \(M_{y_2}M_{y_1} = M_{y_1}^2\Lambda_{x_1}^2\), and \(\Lambda_{x_1} \in \text{SL}(2, \mathbb{Z})\), we conclude that \(\Lambda_{x_2}\) is in \(\text{SL}(2, \mathbb{Z})\). \( \square \)

#### Definition 7.5.

(i) If \(x_2 = \kappa(M_{y_1}M_{y_2})\), then we say that \((M_{y_1}, M_{y_2})\) is a **MM-pair of type I** for \((x_1, x_2; y_1, y_2)\).

(ii) If \(x_2 = \kappa(M_{y_1}M_{y_2})\), then we say that \((M_{y_1}, M_{y_2})\) is a **MM-pair of type II** for \((x_1, x_2; y_1, y_2)\).

#### Example 7.6.

By virtue of (5.1) and Table 4, we can verify that \((M_1, M_3)\) is a MM-pair of type I for \((1, 5; 1, 3)\), \((M_3, M_{11})\) is a MM-pair of type I for \((1, 65; 3, 11)\), \((M_1, M_{17})\) is a MM-pair of type I for \((5, 29; 1, 17)\), and \((M_3, M_{59})\) is a MM-pair of type II for \((5, 349; 3, 59)\).

#### Lemma 7.7.

Let \((x_1, x_2; y_1, y_2)\) be a VS quadruple. Suppose that \(\Lambda_{x_1}, M_{y_1}, \text{and } M_{y_2}\) are associated with \(x_1, y_1, \text{and } y_2\), respectively.

(i) If \((M_{y_1}, M_{y_2})\) is a MM-pair of type I for \((x_1, x_2; y_1, y_2)\), then \(M_{y_2}M_{y_1}\) is a \(\Lambda\)-matrix associated with \(x_2\).

(ii) If \((M_{y_1}, M_{y_2})\) is a MM-pair of type II for \((x_1, x_2; y_1, y_2)\), then \(M_{y_1}M_{y_2}\) is a \(\Lambda\)-matrix associated with \(x_2\).

**Proof.** We here prove (i). Calculate \(M_{y_2}M_{y_1}\):

\[
M_{y_2}M_{y_1} = \frac{1}{2} \left( \begin{array}{cc} \alpha_1\alpha_2 + y_1\beta_2 & \beta_1\alpha_2 + \delta_1\beta_2 \\ \alpha_1y_2 + y_1\delta_2 & \beta_1y_2 + \delta_1\delta_2 \end{array} \right).
\]

Thanks to Lemma 7.4, we have only to check

\[
x_2 = \frac{1}{2} (\alpha_1y_2 + y_1\delta_2) \quad \text{and} \quad \text{tr}(M_{y_2}M_{y_1}) = \frac{1}{2} (\alpha_1\alpha_2 + y_1\beta_2 + \beta_1y_2 + \delta_1\delta_2) = 4x_2.
\]
The former is just equal to \( x_2 = \kappa(M_{y_2}M_{y_1}) \). This is changed into \( 2x_1 = \alpha_2y_1 - \alpha_1y_2 \) by (1.2) and \( \delta_2 = 4y_2 - \alpha_2 
.

The latter is verified by similar computation to the proof of Lemma 7.3. Substituting \( \beta_1, \beta_2, \delta_1, \) and \( \delta_2 \), we get

\[
\text{tr}(M_{y_2}M_{y_1}) = \frac{1}{2y_1y_2} (16\gamma_1^2 \gamma_2^2 - 2(\gamma_1^2 + \gamma_2^2) - (\alpha_2y_1 - \alpha_1y_2)^2).
\]

By virtue of (1.2) and \( 2x_1 = \alpha_2y_1 - \alpha_1y_2 \), this is equal to \( 4x_2 \).

We can prove (ii) in the same way.

\[\square\]

### 7.3. AM-pair and \( A_{x_2} \).

Let \( (\Lambda_{x_1}, \Lambda_{x_2}, M_{y_1}, M_{y_2}) \) be a quadruple of matrices associated with a VS quadruple \((x_1, x_2; y_1, y_2)\). We examine MM-pairs for \((x'_1, x'_2; y'_1, y'_2)\).

**Lemma 7.8.**

(i) If \( (\Lambda_{x_1}, M_{y_2}) \) is a AM-pair of type \( I_a \) (resp. of type \( II_a \)) in \( (\Lambda_{x_1}, \Lambda_{x_2}, M_{y_1}, M_{y_2}) \), then \( (M_{y'_1}, M_{y'_2}) = (M_{y_1}, \Lambda_{x_2}M_{y_2}) \) (resp. \( (M_{y_1}, M_{y_2}) \Lambda_{x_2} \)) is a MM-pair of type \( I \) (resp. of type \( II \)) for the left child of \((x_1, x_2; y_1, y_2)\).

(ii) If \( (\Lambda_{x_2}, M_{y_2}) \) is a AM-pair of type \( I_b \) (resp. of type \( II_b \)) in \( (\Lambda_{x_1}, \Lambda_{x_2}, M_{y_1}, M_{y_2}) \), then \( (M_{y'_1}, M_{y'_2}) = (M_{y_1}, M_{y_2}\Lambda_{x_2}) \) (resp. \( (M_{y_1}, M_{y_2})\Lambda_{x_2} \)) is a MM-pair of type \( II \) (resp. of type \( I \)) for the center child of \((x_1, x_2; y_1, y_2)\).

(iii) If \( (\Lambda_{x_2}, M_{y_1}) \) is a AM-pair of type \( I_c \) (resp. of type \( II_c \)) in \( (\Lambda_{x_1}, \Lambda_{x_2}, M_{y_1}, M_{y_2}) \), then \( (M_{y'_1}, M_{y'_2}) = (M_{y_1}, \Lambda_{x_2}M_{y_2}) \) (resp. \( (M_{y_1}, M_{y_2})\Lambda_{x_2} \)) is a MM-pair of type \( I \) (resp. of type \( II \)) for the right child of \((x_1, x_2; y_1, y_2)\).

**Proof.** Making use of the proof of Lemma 7.3, we here give a proof of (iii) for the case that \( (\Lambda_{x_2}, M_{y_1}) \) is a AM-pair of type \( I_c \) in \( (\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2}) \). The other cases are proved in the same way.

Using

\[
M_{y'_k} = \frac{1}{\sqrt{2}} \begin{pmatrix} \alpha_k' & \beta_k' \\ \gamma_k' & \delta_k' \end{pmatrix}
\]

we verify \( 2x'_k = \alpha_k' y'_k + \gamma_k' \delta_k' \) for \( k = 1, 2 \).

For the right child of \((x_1, x_2; y_1, y_2)\), we have \( x'_2 = 2y_1(4x_2y_1 - y_2) - x_2, y'_1 = y_1 \), and \( y'_2 = 4x_2y_1 - y_2 \). By \( (M_{y'_1}, M_{y'_2}) = (M_{y_1}, \Lambda_{x_2}M_{y_2}) \) and (7.3), we get \( \alpha'_1 = \alpha_1 \) and \( \delta'_2 = x_2\beta_1 + d_2 \delta_1 \). The relation is now written in the following way:

\[
2(2y_2(4x_2y_1 - y_2) - x_2) = \alpha_1(4x_2y_1 - y_2) + y_1(x_2\beta_1 + d_2 \delta_1).
\]

This is directly checked by (7.2), \( \alpha_1\delta_1 - y_1\beta_1 = 2 \), \( \alpha_1 + \delta_1 = 4y_1 \), and \( \alpha_2 + \delta_2 = 4x_2 \).

Combining Lemmas 7.3, 7.7 and 7.8, we obtain the following proposition.

**Proposition 7.9.**

(i) If \( (\Lambda_{x_1}, M_{y_2}) \) is a AM-pair of type \( I_a \) (resp. type \( II_a \)) in \( (\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2}) \), then \( \Lambda_{x_1}M_{y_2}^2 \) (resp. \( M_{y_2}^2 \Lambda_{x_1} \)) is a \( \Lambda \)-matrix associated with \( 2y_2(4x_1y_2 - y_1) - x_1 \).

(ii) If \( (\Lambda_{x_2}, M_{y_2}) \) is a AM-pair of type \( I_b \) (resp. type \( II_b \)) in \( (\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2}) \), then \( M_{y_2}^2 \Lambda_{x_2} \) (resp. \( \Lambda_{x_2}M_{y_2}^2 \)) is a \( \Lambda \)-matrix associated with \( 2y_2(4x_2y_2 - y_1) - x_2 \).

(iii) If \( (\Lambda_{x_2}, M_{y_1}) \) is a AM-pair of type \( I_c \) (resp. type \( II_c \)) in \( (\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2}) \), then \( \Lambda_{x_2}M_{y_1}^2 \) (resp. \( M_{y_1}^2 \Lambda_{x_2} \)) is a \( \Lambda \)-matrix associated with \( 2y_1(4x_2y_1 - y_2) - x_2 \).
Note that (i) corresponds to the case of the left child of \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\), that is, \(\Lambda_{x'_2}\) is defined as either \(\Lambda_x M_{y_2}^2\) or \(M_{y_2}^2 \Lambda_x\), and \(x'_2 = 2y_2(4x_1y_2 - y_1) - x_1\). Likewise, (ii) and (iii) correspond to the case of the center and right child of \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\).

7.4. \(\Lambda M\)-pairs. We have already proved that the matrices \(\Lambda_{x'_2}\) and \(M_{y'_2}\) defined by Algorithm VS from a quadruple \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\) are associated with \(x'_2\) and \(y'_2\), respectively, provided that the pairs of matrices in the quadruple satisfy the hypotheses of Lemma 7.3. In the following, we prove that pairs of \((\Lambda_{x'_1}, \Lambda_{x'_2}; M_{y'_1}, M_{y'_2})\) satisfy these hypotheses.

Corresponding to the proof of Lemmas 7.3 and 7.8, we here discuss the case of the right child of \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\).

**Proposition 7.10.** Let \((x_1, x_2; y_1, y_2)\) be a VS quadruple and let \((x'_1, x'_2; y'_1, y'_2)\) be its right child, that is, \((x'_1, x'_2; y'_1, y'_2) = (x_2, 2y_1(4x_2y_1 - y_2) - x_2; y_1, 4x_2y_1 - y_2)\). Suppose that \((\Lambda_{x_1}, M_{y_1})\) is a \(\Lambda M\)-pair of type \(I_c\) (resp. type \(I_b\)) in \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\) associated with \((x_1, x_2; y_1, y_2)\). Then we have

1. \((\Lambda_{x'_1}, M_{y'_1}) = (\Lambda_{x'_2}, \Lambda_{x_2}; M_{y_1})\) (resp. \((\Lambda_{x'_1}, M_{y'_1}) = (\Lambda_{x'_2}, \Lambda_{x_2}; M_{y_2})\)) is a \(\Lambda M\)-pair of type \(I_a\) (resp. type \(I_a\)) in \((\Lambda_{x'_1}, \Lambda_{x'_2}; M_{y'_1}, M_{y'_2})\);
2. \((\Lambda_{x'_1}, M_{y'_1}) = (\Lambda_{x'_2}, M_{y'_2}, \Lambda_{x_2}; M_{y_1})\) (resp. \((\Lambda_{x'_1}, M_{y'_1}) = (\Lambda_{x'_2}, M_{y'_2}, \Lambda_{x_2}; M_{y_2})\)) is a \(\Lambda M\)-pair of type \(I_b\) (resp. type \(I_b\)) in \((\Lambda_{x'_1}, \Lambda_{x'_2}; M_{y'_1}, M_{y'_2})\);
3. \((\Lambda_{x'_1}, M_{y'_1}) = (\Lambda_{x'_2}, M_{y'_2}, \Lambda_{x_1}; M_{y_1})\) (resp. \((\Lambda_{x'_1}, M_{y'_1}) = (\Lambda_{x'_2}, M_{y'_2}, \Lambda_{x_1}; M_{y_2})\)) is a \(\Lambda M\)-pair of type \(I_c\) (resp. type \(I_c\)) in \((\Lambda_{x'_1}, \Lambda_{x'_2}; M_{y'_1}, M_{y'_2})\).

**Proof.** We here use (7.5) and

\[
\Lambda_{x'_k} = \begin{pmatrix} a'_k & b'_k \\ x'_k & d'_k \end{pmatrix}
\]

for \(k = 1, 2\).

We prove (i) for \((\Lambda_{x'_1}, M_{y'_1}) = (\Lambda_{x'_2}, \Lambda_{x_2}; M_{y_1})\). We have to check \(a'_1y'_2 = x'_1a'_2 + y'_1\).

Since \(a'_2 = a_2\alpha_1 + b_2y_1\) by (7.3), it is written as follows:

\[
a_2(4x_2y_1 - y_2) = x_2(a_2\alpha_1 + b_2y_1) + y_1.
\]

This is verified by (7.2), \(a_2 + d_2 = 4x_2\), and \(a_2d_2 - b_2x_2 = 1\).

Likewise, we can prove the other case of (i).

We prove (iii) for \((\Lambda_{x'_1}, M_{y'_1}) = (\Lambda_{x'_2}, M_{y'_2}; \Lambda_{x_1}; M_{y_1})\). We have to check \(a'_1y'_2 = x'_1a'_2 + y'_1\).

Using (7.4), we compute \(\Lambda_{x_2} M_{y_2}^2\) and get \(a'_2 = a_2(2y_1\alpha_1 - 1) + 2b_2y_1^2\). The relation is then written in the following way:

\[
(a_2(2y_1\alpha_1 - 1) + 2b_2y_1^2)y_1 = (2y_1(4x_2y_1 - y_2) - x_2)\alpha_1 + (4x_2y_1 - y_2).
\]

Using (1.2), (7.2) and \(a_2 + d_2 = x_2\), it is changed into the form

\[
a_2(2y_1\alpha_1 - 1) + 2b_2y_1^2 = \frac{1}{x_2}(2a_2y_1(4x_2y_1 - y_2) - a_2x_2 - 2y_1^2).
\]

This is verified by (7.2), \(a_2 + d_2 = 4x_2\), and \(a_2d_2 - b_2x_2 = 1\).

Likewise, we can prove the other case of (iii).

We prove (ii) for \((\Lambda_{x'_1}, M_{y'_1}) = (\Lambda_{x'_2}, M_{y'_2}; \Lambda_{x_1}; M_{y_1})\). We have to check \(d'_2y'_2 = x'_2\delta'_1 + y'_1\).

In the same way as before, computing \(\Lambda_{x_2} M_{y_2}^2\), we get \(d'_2 = 2x_2y_1\delta_1 + d_2(2y_1\beta_1 - 1)\), and by (7.3) we have \(\delta'_2 = x_2\beta_1 + d_2\delta_1\). The relation is then written in the following way:

\[
(2x_2y_1\beta_1 + d_2(2y_1\delta_1 - 1))(4x_2y_1 - y_2) = (2y_1(4x_2y_1 - y_2) - x_2)(x_2\beta_1 + d_2\delta_1) + y_1.
\]
Using (7.2), \( a_2 + d_2 = 4x_2 \), and \( \alpha_1 \delta_1 - \beta_1 y_1 = 2 \), we get
\[
2x_2y_1\beta_1 + d_2(2y_1\delta_1 - 1) = 2(4x_2y_1 - y_2)\delta_1 - 4x_2 - d_2.
\]
\[
x_2\beta_1 + d_2\delta_1 = \frac{1}{y_1}(4x_2y_1 - y_2)\delta_1 - 2x_2).
\]
Substituting these in (7.6) and using (1.2), (7.2), we know the relation (7.6) is equivalent to the following:
\[
(x_2\delta_1 - d_2y_1)(4x_2y_1 - y_2) = (a_2y_1 - x_2\alpha_1)(4x_2y_1 - y_2) = 2x_2^2 + y_1^2.
\]
Likewise, the other case of (ii) is proved.

In the same way, we can discuss the case of the left and center child of \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\) and prove the followings.

**Proposition 7.11.** Let \((x_1, x_2; y_1, y_2)\) be a VS quadruple and let \((x'_1, x'_2; y'_1, y'_2)\) be its left child, that is, \((x'_1, x'_2; y'_1, y'_2) = (x_1, 2y_2(4x_1y_2 - y_1) - x_1; y_2, 4x_1y_2 - y_1)\). Suppose that \((\Lambda_{x_1}, M_{y_1})\) is a \(\Lambda M\)-pair of type \(I_a\) (resp. type \(I_b\)) in \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\) associated with \((x_1, x_2; y_1, y_2)\). Then we have

(i) \((\Lambda'_{x_1}, M'_{y_1}) = (\Lambda_{x_1}, x_{x_2}, M_{y_2})\) (resp. \((\Lambda_{x_1}, M_{y_2}, \Lambda_{x_1})\) is a \(\Lambda M\)-pair of type \(I_a\) (resp. type \(I_b\)));

(ii) \((\Lambda'_{x_2}, M'_{y_2}) = (\Lambda_{x_2}, M_{y_2}, \Lambda_{x_1}, M_{y_2})\) (resp. \((M_{y_2}^2, \Lambda_{x_1}, M_{y_2}, M_{y_2})\) is a \(\Lambda M\)-pair of type \(I_a\) (resp. type \(I_b\)));

(iii) \((\Lambda'_{x_2}, M'_{y_2}) = (\Lambda_{x_2}, M_{y_2}, \Lambda_{x_2}, M_{y_2})\) (resp. \((M_{y_2}^2, \Lambda_{x_1}, \Lambda_{x_2}, M_{y_2})\) is a \(\Lambda M\)-pair of type \(I_a\) (resp. type \(I_b\)).

**Proposition 7.12.** Let \((x_1, x_2; y_1, y_2)\) be a VS quadruple and let \((x'_1, x'_2; y'_1, y'_2)\) be its center child, that is, \((x'_1, x'_2; y'_1, y'_2) = (x_2, 2y_2(4x_2y_2 - y_1) - x_2; y_2, 4x_2y_2 - y_1)\). Suppose that \((\Lambda_{x_2}, M_{y_2})\) is a \(\Lambda M\)-pair of type \(I_a\) (resp. type \(I_b\)) in \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\) associated with \((x_1, x_2; y_1, y_2)\). Then we have

(i) \((\Lambda'_{x_1}, M'_{y_1}) = (\Lambda_{x_1}, x_{x_2}, M_{y_2}, \Lambda_{x_2})\) (resp. \((\Lambda_{x_2}, \Lambda_{x_2}, M_{y_2})\) is a \(\Lambda M\)-pair of type \(I_a\) (resp. type \(I_b\)));

(ii) \((\Lambda'_{x_2}, M'_{y_2}) = (M_{y_2}^2, \Lambda_{x_2}, M_{y_2}, \Lambda_{x_2})\) (resp. \((\Lambda_{x_2}, M_{y_2}, M_{y_2}, \Lambda_{x_2})\) is a \(\Lambda M\)-pair of type \(I_a\) (resp. type \(I_b\)));

(iii) \((\Lambda'_{x_2}, M'_{y_2}) = (M_{y_2}^2, \Lambda_{x_2}, M_{y_2}, M_{y_2})\) (resp. \((\Lambda_{x_2}, M_{y_2}, M_{y_2})\) is a \(\Lambda M\)-pair of type \(I_a\) (resp. type \(I_b\)).

### 7.5. Proof of Theorem 5.6.
Collecting the preceding results, we complete the proof of Theorem 5.6.

**Lemma 7.13.** Let \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\) be a quadruple of matrices associated with a VS quadruple \((x_1, x_2; y_1, y_2)\).

(i) If \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\) is of type \(I\), then \((\Lambda_{x_1}, M_{y_2})\), \((\Lambda_{x_2}, M_{y_2})\), and \((\Lambda_{x_2}, M_{y_2})\) are \(\Lambda M\)-pairs of type \(I_a\), \(I_b\), and \(I_c\), respectively, in \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\), and \((\Lambda_{y_1}, \Lambda_{y_2})\) is a \(\Lambda M\)-pair of type \(I\) for \((x_1, x_2; y_1, y_2)\).

(ii) If \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\) is of type \(II\), then \((\Lambda_{x_1}, M_{y_2})\), \((\Lambda_{x_2}, M_{y_2})\), and \((\Lambda_{x_2}, M_{y_2})\) are \(\Lambda M\)-pairs of type \(I_a\), \(I_b\), and \(I_c\), respectively, in \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\), and \((\Lambda_{y_1}, \Lambda_{y_2})\) is a \(\Lambda M\)-pair of type \(I\) for \((x_1, x_2; y_1, y_2)\).

**Proof.** We prove this inductively.

For the node \(\mathcal{U}\), \(a, b, c\) in the VS matrix tree, namely, for \((\Lambda_1, \Lambda_5; M_1, M_3)\), \((\Lambda_1, \Lambda_5; M_1, M_3)\), \((\Lambda_5, \Lambda_3; M_1, M_3)\), \((\Lambda_5, \Lambda_3; M_1, M_3)\), and \((\Lambda_5, \Lambda_3; M_1, M_3)\), we can directly verify the claim using (5.1) and Table 4 (see Examples 7.2 and 7.6).
Suppose that \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\) is of type \(I\) and the claim (i) is true. Thanks to Lemma 7.8 and Propositions 7.10, 7.11, and 7.12, we obtain

- its left and right child \((\Lambda_{x'_1}, \Lambda_{x'_2}; M_{y'_1}, M_{y'_2})\) is of type \(I\), and \((\Lambda_{x'_1}, M_{y'_1}), (\Lambda_{x'_2}, M_{y'_2})\) are \(\Lambda M\)-pairs of type \(I_a, I_b, \text{ and } I_c\), respectively, in \((\Lambda_{x'_1}, \Lambda_{x'_2}; M_{y'_1}, M_{y'_2})\), and \((M_{y'_1}, M_{y'_2})\) is a \(MM\)-pair of type \(I\) for \((x'_1, x'_2; y'_1, y'_2)\).
- its center child \((\Lambda_{x'_1}, \Lambda_{x'_2}; M_{y'_1}, M_{y'_2})\) is of type \(II\), and \((\Lambda_{x'_1}, M_{y'_1}), (\Lambda_{x'_2}, M_{y'_2})\) are \(\Lambda M\)-pairs of type \(I_a, I_b, \text{ and } I_c\), respectively, in \((\Lambda_{x'_1}, \Lambda_{x'_2}; M_{y'_1}, M_{y'_2})\), and \((M_{y'_1}, M_{y'_2})\) is a \(MM\)-pair of type \(II\) for \((x'_1, x'_2; y'_1, y'_2)\).

In the same way, if \((\Lambda_{x'_1}, \Lambda_{x'_2}; M_{y_1}, M_{y_2})\) is of type \(II\) and the claim (ii) is true, we obtain

- its left and right child \((\Lambda_{x'_1}, \Lambda_{x'_2}; M_{y'_1}, M_{y'_2})\) is of type \(II\), and \((\Lambda_{x'_1}, M_{y'_1}), (\Lambda_{x'_2}, M_{y'_2})\) are \(\Lambda M\)-pairs of type \(I_a, I_b, \text{ and } I_c\), respectively, in \((\Lambda_{x'_1}, \Lambda_{x'_2}; M_{y'_1}, M_{y'_2})\), and \((M_{y'_1}, M_{y'_2})\) is a \(MM\)-pair of type \(II\) for \((x'_1, x'_2; y'_1, y'_2)\).
- its center child \((\Lambda_{x'_1}, \Lambda_{x'_2}; M_{y'_1}, M_{y'_2})\) is of type \(I\), and \((\Lambda_{x'_1}, M_{y'_1}), (\Lambda_{x'_2}, M_{y'_2})\) are \(\Lambda M\)-pairs of type \(I_a, I_b, \text{ and } I_c\), respectively, in \((\Lambda_{x'_1}, \Lambda_{x'_2}; M_{y'_1}, M_{y'_2})\), and \((M_{y'_1}, M_{y'_2})\) is a \(MM\)-pair of type \(I\) for \((x'_1, x'_2; y'_1, y'_2)\).

The lemma is thus proved. \(\square\)

By virtue of this lemma, we can apply Lemma 7.7 and Proposition 7.9 to each quadruple of matrices in the VS matrix tree. Finally, we conclude that, if \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\) is associated with \((x_1, x_2; y_1, y_2)\), then \((\Lambda_{x'_1}, \Lambda_{x'_2}; M_{y'_1}, M_{y'_2})\) is also associated with \((x'_1, x'_2; y'_1, y'_2)\).

Hence, Theorem 5.6 is proved.

7.6. Proof of Theorem 5.12. Let \(\Lambda_1\) and \(M_m\) be matrices in the VS matrix tree. Thanks to Corollary 5.7, we can suppose that \(\Lambda_1\) is associated with \(\lambda \in N(\Lambda)\) and \(M_m\) is associated with \(m \in N(M)\). Recall basic facts: trace and determinant are invariant on conjugacy classes, that is,

\[
\text{tr}(D) = \text{tr}(C^{-1}DC) \quad \text{and} \quad \det(D) = \det(C^{-1}DC) \quad \text{for } C, D \in \text{SL}(2, \mathbb{C}).
\]

It follows from (5.5) and these facts that \(\text{tr}(\Lambda_1) = \text{tr}(\tilde{\Lambda}_1) = 4\lambda\), \(\text{tr}(M_m) = \text{tr}(\tilde{M}_m) = 2\sqrt{2}m\), \(\det(\Lambda_1) = \det(\tilde{\Lambda}_1) = 1\), and \(\det(M_m) = \det(M_m) = 1\). Hence, to prove Theorem 5.12, we will check the forms of matrices \(\Lambda_1\) and \(M_m\).

We can directly verify that \(\Lambda_1\) and \(\tilde{\Lambda}_1\) are \(\Lambda\)-matrices associated with 1 and 5 and that \(\tilde{M}_1\) and \(\tilde{M}_3\) are \(\tilde{M}\)-matrices associated with 1 and 3 (see (5.4) and Table 5). We check the forms of matrices by induction. Let \((x_1, x_2; y_1, y_2)\) be a VS quadruple and let \((x'_1, x'_2; y'_1, y'_2)\) be a child of \((x_1, x_2; y_1, y_2)\). Recall that the parent has three children. For a quadruple of complex matrices \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\), we suppose that \(\tilde{\Lambda}_{x_1}\) is associated with \(x_1\), \(\tilde{\Lambda}_{x_2}\) with \(x_2\), \(\tilde{M}_{y_1}\) with \(y_1\), and \(\tilde{M}_{y_2}\) with \(y_2\). Equivalently, in the VS matrix tree there exists a quadruple of real matrices \((\Lambda_{x_1}, \Lambda_{x_2}; M_{y_1}, M_{y_2})\) associated with \((x_1, x_2; y_1, y_2)\).
Recall that $\tilde{\lambda}_{x_2}$ is defined as either $\tilde{\lambda}_{x_1} \tilde{M}_{y_1}$ or $\tilde{M}_{y_1} \tilde{\lambda}_{x_1}$ (see Remark 5.4). We here describe $\tilde{M}_{y_1}$ by the following form:

\[(7.7) \quad \tilde{M}_{y_1} = \frac{1}{\sqrt{2}} \begin{pmatrix} \alpha_1' + y_1' i & \beta_1' + \gamma_1' i \\ 2y_1' i & 2 \end{pmatrix},\]

where $\alpha_1'$, $\beta_1'$, $\gamma_1'$, and $\delta_1'$ are some integers. Since $y_1' = y_1$ or $y_2$, by inductive hypothesis, $\tilde{M}_{y_1}$ is associated with $y_1'$. Using $\text{tr}(\tilde{M}_{y_1}) = 2\sqrt{2}y_1'$ and $\det(\tilde{M}_{y_1}) = 1$, we get

\[\tilde{M}_{y_1}^2 = \frac{1}{4(y_1')^2} \begin{pmatrix} 2y_1'(\alpha_1' + \beta_1' i) & 2y_1'(\beta_1' + \gamma_1' i) \\ 2y_1' \beta_1' - 1 + y_1'(\beta_1' - \delta_1' i) i & 2 \end{pmatrix} \begin{pmatrix} \alpha_1' + y_1' i & 2y_1'(\beta_1' + \gamma_1' i) \\ 2y_1' \beta_1' - 1 + y_1'(\beta_1' - \delta_1' i) i & 2 \end{pmatrix}
\]

We thus know $\tilde{M}_{y_1}^2$ is an element of $\text{SL}(2, \mathbb{Z}[i])$. By virtue of $\tilde{\lambda}_{x_1} \in \text{SL}(2, \mathbb{Z}[i])$, the matrix $\tilde{\lambda}_{x_2}$ must be in $\text{SL}(2, \mathbb{Z}[i])$.

By inductive hypothesis and Corollary 5.7, $\tilde{L}_{x_2}$ is associated with $x_2'$ and $M_{y_2}^\prime$ is associated with $y_2'$. These matrices can then be described in the following way:

\[
\tilde{\lambda}_{x_2} = \begin{pmatrix} a_2' & b_2' \\ x_2' & d_2' \end{pmatrix} \quad \text{and} \quad \text{tr}(\tilde{\lambda}_{x_2}) = 4x_2',
\]

\[
M_{y_2}^\prime = \frac{1}{\sqrt{2}} \begin{pmatrix} a_2' & \beta_2' \\ y_2' & \delta_2' \end{pmatrix} \quad \text{and} \quad \text{tr}(M_{y_2}^\prime) = 2\sqrt{2}y_2',
\]

where $a_2'$, $b_2'$, $d_2'$, $\alpha_2'$, $\beta_2'$, and $\delta_2'$ are some integers. We calculate their conjugates:

\[
\tilde{\lambda}_{x_2} = V^{-1}\tilde{\lambda}_{x_2}^\prime V = \begin{pmatrix} a_2' + x_2' i & \frac{1}{2}((d_2' - a_2') - (b_2' + x_2') i) \\ 2x_2' i & d_2' - x_2' i \end{pmatrix},
\]

\[
\tilde{M}_{y_2}^\prime = V^{-1}M_m V = \frac{1}{\sqrt{2}} \begin{pmatrix} a_2' + y_2' i & \frac{1}{2}((\delta_2' - a_2') - (y_2' + \beta_2') i) \\ 2y_2' i & \delta_2' - y_2' i \end{pmatrix}.
\]

The $(2,1)$-entries of these satisfy the conditions of Definition 5.10. We have already proved that $\tilde{\lambda}_{x_2}$ is in $\text{SL}(2, \mathbb{Z}[i])$, so the $(1,2)$-entry of $\tilde{\lambda}_{x_2}$ is a Gaussian integer. Since $\tilde{M}_{y_2}^\prime$ is defined as either $\tilde{\lambda}_{x_2} M_{y_1}^\prime$ or $M_{y_1}^\prime \tilde{\lambda}_{x_1}$ (see also Remark 5.4), by $\tilde{\lambda}_{x_1} \in \text{SL}(2, \mathbb{Z}[i])$ and $(7.7)$, we easily know $(1/2)((\delta_2' - a_2') - (y_2' + \beta_2') i)$ is also a Gaussian integer.

Theorem 5.12 is thus proved.

References

Tokyo Polytechnic University, Atsugi, Kanagawa 243-0297, Japan
E-mail address: ryu2abe@email.plala.or.jp

University of Melbourne, Department of Mathematics
E-mail address: I.Aitchison@ms.unimelb.edu.au