Explicit Free Parameterization of the Modified 
Tetrahedron Equation

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Abstract. The Modified Tetrahedron Equation (MTE) with affine Weyl quantum 
variables at $N$-th root of unity is solved by a rational mapping operator which is 
obtained from the solution of a linear problem. We show that the solutions can be 
parameterized in terms of eight free parameters and sixteen discrete phase choices, 
thus providing a broad starting point for the construction of 3-dimensional integrable 
lattice models. The Fermat curve points parameterizing the representation of the 
mapping operator in terms of cyclic functions are expressed in terms of the independent 
parameters. An explicit formula for the density factor of the MTE is derived. For the 
example $N = 2$ we write the MTE in full detail. We also discuss a solution of the 
MTE in terms of bosonic continuum functions.

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Introduction

The Zamolodchikov tetrahedron equation is the condition \[ \Box \] for the existence of a 
commuting set of layer-to-layer transfer matrices for 3-dimensional lattice models, in 
much the same way as the Yang-Baxter equation is the analogous condition in the 2-
dimensional case. Only very few solutions to these very restrictive equations have been 
found \[ \Box \]. So various Modified Tetrahedron Equations (MTE) have been studied to 
which more solutions can be obtained \[ \Box \], still leading to commuting transfer 
matrices or generating functionals for conserved quantities.

In this paper we shall concentrate on a particular MTE proposed in \[ \Box \]. The 
quantum variables are elements from an ultra-local affine Weyl algebra attached to 
every vertex of a 2-dimensional graph. Since we consider the Weyl parameter to be a 
$N$-th root of unity, the $N$-th powers of the quantum variables form a classical system
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which determines the parameters of the quantum system, as has been considered in for
the discrete sin-Gordon model and other models recently, e.g. [11, 12, 13, 14]. So the
parameters of the eight \( R \) matrices appearing in the MTE are different, but related by
functional mappings.

A linear problem discussed previously by one of us [9, 10], is used to determine
the mapping which provides a multi-parameter solution to the MTE. The construction
of a generating functional of the conserved quantities has been given in [9]. Here we
concentrate on calculating the density factor of the MTE and to give a useful choice of
the eight continuous parameters of the mapping.

The aim of studying these equations is at least two-fold: first a 2+1-dimensional
integrable lattice model should emerge, and second, the MTE can be used by contraction
[15] to construct new 2-dimensional lattice models with parameters living on higher
Riemann surfaces.

The paper is organized as follows: In Sec.1 we introduce the rational mapping in the
affine Weyl space and show that if the Weyl parameter is a root of unity this splits into a
matrix mapping and a functional mapping. Then we consider two different realizations:
in terms of cyclic functions (this will be mainly used) and in terms of Gaussians. Sec.
2 discusses the modified tetrahedron equation and we calculate its weight function. In
Sec. 3 we focus on the parameterization in terms of line ratios, finding eight continuous
parameters and analyze the phase ambiguities. For the specific case \( N = 2 \) in Sec. 4 we
show that the modified tetrahedron equations can be written quite explicitly and that
of their 2^{12} matrix components there are 256 linearly independent equations. In Sec. 5
we give a summary and mention future applications.

1. The rational mapping \( \mathcal{R} \) in the space of a triple affine Weyl algebra.

The central object of our considerations will be a mapping operator acting in the
space of a triple Weyl affine algebra. We shall see that this mapping operator can be
written as a superposition of a functional mapping and a finite-dimensional similarity
transformation. It is the operator of this similarity transformation which will satisfy
the MTE. Several interpretations are possible, e.g. as vertex Boltzmann weights (albeit
not positive ones) of a three-dimensional lattice model. It will be a generalization of the
Zamolodchikov-Bazhanov-Baxter [1, 2] Boltzmann weights in the Sergeev-Mangazeev-
Stroganov [4] vertex formulation. The principle from which this mapping is obtained
has been described in detail in [9]. It is a current conservation principle with a Baxter
Z-invariance.

1.1. The linear problem.

To set the framework we assign to each vertex \( j \) of a 2d graph the elements \( u_j, w_j \) of
an affine Weyl algebra at Weyl parameter \( q \) a root of unity:

\[
 u_j \cdot w_j = q w_j \cdot u_j, \quad q = \omega \stackrel{\text{def}}{=} e^{2\pi i/N}, \quad N \in \mathbb{Z}, \quad N \geq 2.
\]  

(1)
Since $q$ is a root of unity, $u_j^N$ and $w_j^N$ are centers of the Weyl algebra. We shall often represent the canonical pair $(u_j, w_j)$ by its action on a cyclic basis as unitary $N \times N$ matrices multiplied by complex parameters $u_j, w_j$, writing

$$u = u x; \quad w = w z;$$

$$|\sigma\rangle \equiv |\sigma \mod N\rangle; \quad \langle \sigma | \sigma'\rangle = \delta_{\sigma,\sigma'}; \quad x |\sigma\rangle = |\sigma\rangle \omega^\sigma; \quad z |\sigma\rangle = |\sigma + 1\rangle. \quad (3)$$

The centers are represented by numbers:

$$u_j^N = u_j^N, \quad w_j^N = w_j^N. \quad (4)$$

We define the ultra-local Weyl algebra $\mathfrak{w}^\otimes \Delta$ as the tensor product of $\Delta$ copies of Weyl pairs

$$u_j = 1 \otimes 1 \otimes ... \otimes \underline{u}_{j-th \ place} \otimes ...; \quad w_j = 1 \otimes 1 \otimes ... \otimes \underline{w}_{j-th \ place} \otimes ... . \quad (5)$$

Denote the four faces around the vertex $j$ (in which two oriented lines cross) clockwise by $a, b, c, d$ as e.g. shown in the left side of Fig. 1 for the vertex $j = 3$. Imagine a current $\langle \phi |$ flowing out of the vertex into the four faces $a, b, c, d$, each face receiving a current $\langle \phi_s |$ ($s = a, b, c, d$) according to the values of the Weyl variables sitting at the vertex and a coupling constant $\kappa_j$ (which may be different at each vertex):

$$\langle \phi | = \langle \phi_a | + \langle \phi_b | \cdot q^{1/2} u_j + \langle \phi_c | \cdot w_j + \langle \phi_d | \cdot \kappa_j u_j w_j. \quad (6)$$

Demanding that the total current flowing out of an internal vertex is zero: $\langle \phi | = 0$, and demanding also that the currents flowing into the outer faces of various graphs are independent of the internal structure of the graphs (this is a Z-invariance assumption), we get a condition for the equivalence of linear problems. The right hand side of Fig.1 shows two such linear problems, one in the bottom plane, another in the upper plane. The equivalence condition determines the mapping $R_{1,2,3}$ between the lower ($w_1, w_2, w_3$) and upper ($w'_1, w'_2, w'_3$) triangle in Fig. 1 uniquely. The details of this calculation can be found in [9]; in (7)-(9) below we present the result.

For our case of interest $q = \omega$ it is convenient to choose the specific form (6) of the coefficients, which is unsymmetrical in $a, b, c, d$. There exists a fully symmetrical formulation of the linear problem valid at general $q$, still leading to a unique mapping $R_{1,2,3}$. However, this will not be needed here.

1.2. The rational mapping $R_{1,2,3}$

The solution of the equivalence problem of the linear current flows is the following rational mapping $R_{1,2,3}$ acting in the ring of rational functions of the generators of the ultra-local Weyl algebra $\mathfrak{w}$: For any rational function $\Phi$ we define

$$(R_{1,2,3} \circ \Phi)(u_1, w_1, u_2, w_2, u_3, w_3, ...) \overset{def}{=} \Phi(u'_1, w'_1, u'_2, w'_2, u'_3, w'_3, ...). \quad (7)$$
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\begin{align}
\phi_a & \quad \phi_b \\
\phi_c & \quad \phi_d
\end{align}

Figure 1. The linear problem for the vertex with associated Weyl pair \(u_3, w_3\) and parameter \(\kappa_3\) and the visualization of \(R_{1,2,3}\). The elements \(w_1, w'_1,\) etc. of the ultralocal affine Weyl algebras are assigned to the vertices of two auxiliary two dimensional lattices formed by the intersection of three straight lines with the auxiliary planes.

where in the right hand side of (7) the \(u_\alpha\) and \(w_\alpha\) remain unchanged for all \(\alpha \notin \{1, 2, 3\}\), and the primed elements are rational functions of \(u_1, u_2, w_1, w_3\), given by the definition

\begin{align}
\Lambda_1 & \equiv u^{-1}_1 \cdot u_3 - q^{1/2} u^{-1}_1 \cdot w_1 + \kappa_1 w_1 \cdot u^{-1}_2, \\
\Lambda_2 & \equiv \frac{\kappa_1}{\kappa_2} u^{-1}_2 \cdot w^{-1}_3 + \frac{\kappa_3}{\kappa_2} u^{-1}_1 \cdot w^{-1}_2 - q^{-1/2} \frac{\kappa_1 \kappa_3}{\kappa_2} u^{-1}_2 \cdot w^{-1}_2, \\
\Lambda_3 & \equiv w_1 \cdot w^{-1}_3 - q^{1/2} u^{-1}_3 \cdot w^{-1}_3 + \kappa_3 w^{-1}_2 \cdot u_3.
\end{align}

\(\kappa_1, \kappa_2, \kappa_3 \in \mathbb{C}\) are arbitrary extra parameters of the mapping \(R_{1,2,3}\). In this subsection \(q\) can be in general position.

Note that the order of the factors in the right hand sides of (8) does not matter. Each combination \(\Lambda_i\) \((i = 1, 2, 3)\) contains only elements of the Weyl algebra which commute with the other factors in the product. For example, \(\Lambda_3\) does not have the Weyl operators \(u_1\) and \(u_2\). From (8) we see that the rational mapping \(R_{1,2,3}\) has the three invariants:

\begin{align}
w_1 w_2, \quad u_2 u_3, \quad u_1 w_3^{-1}.
\end{align}

This means that this mapping has the property that the products \(u_j^{-1} u_j'\) and \(w_j^{-1} w_j'\) for \(j = 1, 2, 3\) (no summation over \(j\)) depend only on three operators which we denote by \(u, v\) and \(w\):

\begin{align}
u = w_2^{-1} w_3; \quad v = u_1 u_2^{-1}; \quad w = w_1 u_3^{-1}.
\end{align}
as one easily checks explicitly:

\[(w_3^{-1}w_3')^{-1} = (u_1^{-1}u_1')^{-1} = u_1\Lambda_2 w_3 = \frac{\kappa_1}{\kappa_2} v + \frac{\kappa_3}{\kappa_2} u - q^{-1/2} \frac{\kappa_1 \kappa_3}{\kappa_2} vu;
\]

\[(u_2^{-1}u_2')^{-1} = u_3^{-1}u_3' = u_3^{-1}\Lambda_1 u_2 = v^{-1} + \kappa_1 w - q^{1/2} v^{-1} w;
\]

\[w_1^{-1}w_1' = (w_2^{-1}w_2')^{-1} = w_2\Lambda_3 w_1^{-1} = u^{-1} + \kappa_1 w^{-1} - q^{1/2} w^{-1} u^{-1}.
\] (12)

Observe that the three operators \([12, 13, 14]\) form a triple Weyl algebra: \(vu = q uv, \quad vw = q vw, \quad uw = q wu\), and also at each vertex \(j\) we can regard \(u_j, w_j\) together with \(v_j \equiv \kappa_j u_j w_j\) as forming triple Weyl algebras.

The mapping \(R\) has the property (see \([1, 3, 10, 11, 13]\) for the details):

**Proposition 1** The invertible mapping \(R_{i,j,k}\) is an automorphism of \(W_{\otimes \Delta}\).

**Remark 1** The Proposition states that the rational mapping (8) is canonical, namely, it sends three copies of the ultra-local Weyl algebras into the same Weyl algebras.

Later, in Sec. 1.3, Proposition 4, we shall discuss the second crucial property of the mapping \(R\): it solves the Tetrahedron Equation (19).

**1.3. Functional part at root of unity**

In all the following we shall consider only the case that \(q\) is a root of unity (1) and use the unitary representation (3) of \(W_{\otimes \Delta}\). In this representation each affine Weyl element \(u_j\) and \(w_j\) will contain one free parameter \(u_j\) resp. \(w_j\), as written in (2).

The basic fact is that at Weyl parameter root of unity any rational automorphism of the ultra-local Weyl algebra implies a rational mapping in the space of the \(N\)-th powers of the parameters of the representation \([12, 13, 14]\). In our case (8) it is easy to check that the mapping \(R_{1,2,3}\) implies

\[
w_1^N = w_2^N \Lambda_3^N, \quad w_2^N = \frac{w_1^N}{\Lambda_3^N}, \quad w_3^N = \frac{1}{\Lambda_2^N u_1^N}, \quad u_1^N = \frac{1}{\Lambda_2^N w_3^N}, \quad u_2^N = \frac{u_3^N}{\Lambda_1^N}, \quad u_3^N = u_2^N \Lambda_1^N,
\] (13)

where the \(N\)-th powers of the \(\Lambda_k\) are also numbers:

\[
\Lambda_1^N = u_1^{-N} u_3^N + u_1^{-N} w_1^N + \kappa_1^N w_1^N u_2^{-N},
\]

\[
\Lambda_2^N = \frac{\kappa_1^N}{\kappa_2} u_2^{-N} w_3^{-N} + \frac{\kappa_3^N}{\kappa_2} u_1^{-N} w_2^{-N} + \frac{\kappa_1^N \kappa_3^N}{\kappa_2^2} u_2^{-N} w_2^{-N}, \quad \Lambda_3^N = w_1^N w_3^{-N} + u_3^N w_3^N + \kappa_3^N w_2^{-N} u_3^N
\] (14)

since for \(q = \omega\) and \(a, b \in \mathbb{C}\) one has \((a u + b w)^N = (a u)^N + (b w)^N\), using \(\sum_{j=2}^{N-1} \omega^j = 0\).
The rational mapping (8) for the set of matrices (19) has the form
\[ w = \Gamma (u_1, w_1, u_2, w_2, u_3, w_3) \]
where the primed variables are functions of the unprimed ones, defined via
\[ u_1^N = u_1^N, \quad w_1^N = w_1^N, \quad \text{etc.} \]
such that the \( u_j, w_j, u_j', w_j' \) satisfy
\[ u_1'w_2 = w_1w_2, \quad u_2'u_3 = u_2u_3, \quad \frac{u_1'}{w_3'} = \frac{u_1}{w_3}. \]

The three free phases of the \( N \)-th roots are extra discrete parameters of \( \mathcal{R}_{1,2,3}^{(f)} \).

We use the invariance of the three centers \( u_2u_3, u_1/w_3 \) and \( w_1w_2 \) to define three functions \( \Gamma_1, \Gamma_2, \Gamma_3 \):
\[
\begin{align*}
\Gamma_1^N &= \frac{u_3^N}{w_3^N} = \frac{u_2^N}{w_2^N} = (u_3^1\Lambda_1u_2)^N = \frac{u_3^N}{u_1^N} + \frac{w_1^1u_2^N}{w_1^3u_3^3} + \kappa_1^Nu_1^N, \\
\Gamma_2^N &= \frac{w_3^N}{w_1^N} = \frac{w_3^N}{w_2^N} = (w_3\Lambda_2u_1)^N = \frac{\kappa_1^N}{\kappa_2^N} \frac{w_1^N}{w_2^N} + \frac{\kappa_3^N}{\kappa_2^N} \frac{w_1^N}{w_3^N} + \frac{\kappa_1^N\kappa_2^N}{\kappa_2^N} \frac{u_1^N}{w_2^N}, \\
\Gamma_3^N &= \frac{w_1^N}{w_1^N} = \frac{w_2^N}{w_3^N} = (w_3^{-1}\Lambda_3w_2)^N = \frac{w_2^N}{w_3^N} + \frac{w_2^N}{w_3^N} + \frac{\kappa_3^N}{w_1^N}.
\end{align*}
\]

so that, alternatively to using (13), (14), the functional mapping can be written as
\[
\begin{align*}
\mathcal{R}^{(f)} \circ w_1 &= w_1\Gamma_3, \quad \mathcal{R}^{(f)} \circ w_2 = \frac{w_2}{\Gamma_3}, \quad \mathcal{R}^{(f)} \circ w_3 = \frac{w_3}{\Gamma_2}, \\
\mathcal{R}^{(f)} \circ u_1 &= \frac{u_1}{\Gamma_2}, \quad \mathcal{R}^{(f)} \circ u_2 = \frac{u_2}{\Gamma_1}, \quad \mathcal{R}^{(f)} \circ u_3 = u_3\Gamma_1.
\end{align*}
\]

The \( \Gamma_j \) depend on 3 variables and the 3 constants \( \kappa_j \). Their phases are arbitrary.

1.4. Matrix part at root of unity

Now we consider the matrix structure of \( \mathcal{R}_{1,2,3} \) at \( q \) a root of unity. First of all, we define
\[
x_1' = \frac{u_1'}{u_1}, \quad z_1' = \frac{w_1'}{w_1}, \quad \text{etc.} \quad (19)
\]
The normalization implies the conservation of the centers
\[
x_1^N = x_2^N = 1, \quad z_1^N = z_2^N = 1, \quad \text{etc.} \quad (20)
\]
The rational mapping (8) for the set of matrices (19) has the form
\[
\begin{align*}
(x_1')^{-1} &= \frac{\kappa_1^1u_1'}{\kappa_2^2u_2} - x_2^{-1} + \frac{\kappa_3^1u_1'w_3}{\kappa_2^2u_2w_2} x_1^{-1} - z_3^{-1}, \\
z_1' &= \frac{w_2u_1}{w_1w_3} z_1 z_2 z_3^{-1} - \omega^{1/2} \frac{w_2u_3}{w_1w_3} z_2 z_3^{-1} + \frac{\kappa_3^3}{w_1^N} x_3,
\end{align*}
\]
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\[(x'_2)^{-1} = \frac{u'_1}{u_1}x_1^{-1} - \omega^{1/2}\frac{w_1u'_2}{u_1u_3}x_1^{-1}z_1x_3^{-1} + \frac{\kappa_2w_1u'_2}{u_2u_3}z_1x_2^{-1}x_3^{-1}, \tag{21}\]

\[(z'_2)^{-1} = \frac{w'_2}{w_2}z_3^{-1} - \omega^{1/2}\frac{w'_2u_3}{w_1u_3}z_1^{-1}x_3z_3^{-1} + \frac{\kappa_3w'_2u_3}{w_1u_2}z_1^{-1}z_2^{-1}x_3,\]

\[x'_3 = \frac{u_2u_3}{u_1u_7}x_1^{-1}x_2x_3 - \omega^{1/2}\frac{w_1u_2}{u_1u'_3}x_1^{-1}z_1x_2 + \frac{\kappa_2w_1}{u'_3}z_1,\]

\[(z'_3)^{-1} = \frac{\kappa_1u_1u'_3}{\kappa_2u_2u_3}x_1x_2^{-1}z_3^{-1} + \frac{\kappa_3w'_3}{\kappa_2w_2}z_2^{-1} - \omega^{1/2}\frac{\kappa_1\kappa_3u_1u'_2}{\kappa_2u_2u_2}x_1x_2^{-1}z_2^{-1}.\]

This mapping \(x_j, z_j \mapsto x'_j, z'_j, j = 1, 2, 3,\) is the basic example of a class of the canonical rational mappings of the ultra-local Weyl algebra. The following lemma establishes the uniqueness of the matrix structure of any such mapping.

**Lemma 1** Let \(x_j, z_j, j = 1 \ldots \Delta\) be a normalized finite-dimensional unitary basis \((3)\) of the local Weyl algebra

\[x_i z_j = q z_j x_i \delta_{i,j}; \quad q^N = 1; \quad x_j^N = z_j^N = 1. \tag{22}\]

Let \(E: x_j, z_j \mapsto x'_j, z'_j\) be an invertible canonical mapping in the space of rational functions of \(x_j, z_j\) such that it conserves the centers

\[x_j'^N = z_j'^N = 1.\]

Then there exists a unique (up to a scalar multiplier) \(N^\Delta \times N^\Delta\) matrix \(E\) such that for any \(\Phi\) of eq. \((\mathbb{I})\):

\[\Phi(x'_j, z'_j) = E \Phi(x_j, z_j) E^{-1}. \tag{23}\]

**Proof:** The ring of the rational functions of \(x_j, z_j\) at root of unity is the algebra of the polynomials of \(x_j, z_j\) with \(\mathbb{C}\)-valued coefficients. Evidently this enveloping algebra is the complete algebra of \(N^\Delta \times N^\Delta\) matrices. Since \(E\) is invertible, the envelope of \(x'_j, z'_j\) is the same matrix algebra. Furthermore, since \(E\) is canonical and conserves the \(N\)-th powers of the Weyl elements, \(E\) is an automorphism of the matrix algebra. Finally, since the algebra of \(N^\Delta \times N^\Delta\) matrices is the irreducible fundamental representation of the semi-simple algebra \(gl(N^\Delta)\), any such automorphism is an internal one and may be realized by the unique matrix \(E\) of \((\mathbb{I})\).

\[\square\]

**1.5. Matrix part of \(R_{1,2,3}\) at root of unity in terms of Fermat curve cyclic functions \(W_p(n)\)**

Due to lemma \((\mathbb{I})\) there exists a unique (up to a scalar factor) \(N^3 \times N^3\)-dimensional matrix \(R_{1,2,3}\), such that

\[R_{1,2,3}x_1 = x'_1 R_{1,2,3}, \quad R_{1,2,3}z_1 = z'_1 R_{1,2,3}, \quad \text{etc.} \tag{24}\]

for \((21)\).
The basis independent expression for $R_{1,2,3}$ is not a useful object, and here we give the matrix elements of $R_{1,2,3}$ in the basis $|j_1, j_2, j_3\rangle$ in terms of the Bazhanov-Baxter [2] cyclic functions $W_p(x)$ which we shall mainly use in this paper. We define

$$\frac{W_p(n)}{W_p(n-1)} = \frac{y}{1 - \omega^n x}; \quad W_p(0) = 1,$$

where $n \in \mathbb{Z}_N$ and $p = (x, y)$ denotes a point on the Fermat curve $x^N + y^N = 1$.

For $n > 0$ we have

$$W_p(n) = \prod_{\nu=1}^n \frac{y}{1 - \omega^{\nu} x}. \quad (27)$$

and generally $W_p(n + N) = W_p(n)$, because of $\prod_{\nu=0}^{N-1} (1 - \omega^{\nu} x) = y^N$. One automorphism of the Fermat curve will be important for later calculations. Defining $Op$ by

$$p = (x, y) \mapsto Op = (\omega^{-1} x^{-1}, \omega^{-1/2} x^{-1} y), \quad (28)$$

we have

$$W_p(n) = \frac{1}{W_{Op}(-n) \Phi(n)}; \quad (29)$$

with

$$\Phi(n) = (-1)^n \omega^{n^2/2}. \quad (30)$$

At special points on the Fermat curve the $W_p(n)$ take simple values: Defining

$q_0 = (0, 1); \quad q_\infty = O q_0; \quad q_1 = (\omega^{-1}, 0); \quad (31)$

we get

$$W_{q_0}(n) = 1; \quad W_{q_\infty}(n) = \Phi^{-1}(n); \quad \frac{1}{W_{q_1}} = \delta_{n,0}. \quad (32)$$

We now express our conjugation matrix in terms of the functions $W_p(n)$:

**Proposition 2** In the basis $|j_1, j_2, j_3\rangle$ the matrix $R_{1,2,3}$, solving the relations (27,24), has the following matrix elements:

$$\langle i_1, i_2, i_3 | R_{1,2,3} | j_1, j_2, j_3 \rangle \stackrel{\text{def}}{=} R_{i_1, i_2, i_3}^{j_1, j_2, j_3} = \delta_{i_2+i_3, j_2+j_3} \omega^{(j_1-i_1)j_3} \frac{W_{p_1}(i_2-i_1) W_{p_2}(j_2-j_1)}{W_{p_3}(j_2-i_1) W_{p_4}(i_2-j_1)}, \quad (33)$$

where the $x$-coordinates of the four Fermat curve points are connected by

$$x_1 x_2 = \omega \ x_3 x_4. \quad (34)$$

In the terms of the variables $u_j, w_j, \kappa_j$, $j = 1, 2, 3$, these points are defined by

$$x_1 = \frac{\omega^{-1/2} u_2}{\kappa_1 u_1}, \quad x_2 = \omega^{-1/2} \kappa_2 \frac{u'_2}{u'_1}, \quad x_3 = \omega^{-1/2} \frac{u'_3}{u'_1}, \quad x_4 = \omega^{-1/2} \kappa_2 \frac{u_2}{\kappa_1 u_1}, \quad (35)$$

$$\frac{y_3}{y_1} = \kappa_1 \frac{w_1}{w'_3}, \quad \frac{y_4}{y_1} = \omega^{-1/2} \kappa_3 \frac{w_3}{w_2}, \quad \frac{y_3}{y_2} = \frac{w'_2}{w_3}, \quad \frac{y_4}{y_2} = \omega^{-1/2} \kappa_3 \frac{u'_3}{u'_1}. \quad (36)$$
where the \( u'_j, w'_j \) and \( u_j, w_j \) are related by the functional transformation (13):

\[
\begin{align*}
\forall j & : u'_j = \mathcal{R}_{1,2,3}^{(f)} \circ u_j, \\
\forall j & : w'_j = \mathcal{R}_{1,2,3}^{(f)} \circ w_j. 
\end{align*}
\] (37)

**Proof.** We shall give the proof, that (33) produces the rational mapping, for the first line of (21) only, the other equations follow analogously.

First observe that the matrix elements of the operator \( \mathbf{R}_{1,2,3} \) satisfy several recurrent relations. In particular, we will need the recursion

\[
R_{i_1,i_2+1,i_3-1}^{j_1,j_2,j_3} = R_{i_1,i_2,i_3}^{j_1,j_2,j_3} \cdot \frac{y_1}{y_4} \cdot \frac{1 - \omega^{i_2 - j_1 + 1} x_4}{1 - \omega^{j_1 - i_2 + 1} x_1}
\]

which can be rewritten in the form

\[
R_{i_1,i_2,i_3}^{j_1,j_2,j_3} \omega^{-j_1} = \frac{1}{\omega^{i_2 + 1} x_4} R_{i_1,i_2,i_3}^{j_1,j_2,j_3} + \frac{x_1 y_4}{\omega y_1 x_4} R_{i_1,i_2+1,i_3-1}^{j_1,j_2,j_3} - \frac{y_4}{\omega y_1 x_4} R_{i_1,i_2+1,i_3-1}^{j_1,j_2,j_3}.
\] (38)

However, this recurrent relation is the matrix element \( \langle i_1 i_2 i_3 | \cdot | j_1 j_2 j_3 \rangle \) of the operator equality

\[
\mathbf{R}_{1,2,3} \cdot (x'_1)^{-1} = \left( \frac{1}{\omega x_4} x_2^{-1} + \frac{x_1 y_4}{y_1 x_4} x_1^{-1} z_2^{-1} z_3 - \frac{y_4}{\omega y_1 x_4} x_2^{-1} z_2^{-1} z_3 \right) \cdot \mathbf{R}_{1,2,3}.
\]

This coincides with the first line in (21), provided the identification (33) and (16) is valid for the Fermat points \((x_1,y_1)\) and \((x_4,y_4)\). \(\square\)

**Remark 2** \( \mathbf{R} \) is a matrix function of three continuous parameters \( x_1, x_2, x_3 \) and three discrete parameters: the phases of \( y_1, y_2, y_3 \). Equivalently, one may use \( \kappa_1, w_1 \), \( \kappa_2, w_2 \), and \( \kappa_3, w_3 \) as the continuous parameters and the phases of \( u'_1, u'_2, u'_3 \) as the discrete parameters. Formulas (33,34) establish the correspondence between these choices. We call the parameterization of \( \mathbf{R}_{1,2,3} \) in the terms of \( u_j, w_j, \kappa_j \) a "free parameterization".

**Remark 3** Formulated in terms of mappings, the automorphism \( \mathbf{R}_{1,2,3} \) of the ultralocal Weyl algebra at the root of unity is presented as the superposition of a pure functional mapping and the finite dimensional similarity transformation:

\[
\mathbf{R}_{1,2,3} \circ \Phi = \mathbf{R}_{1,2,3} \left( \mathcal{R}_{1,2,3}^{(f)} \circ \Phi \right) \mathbf{R}_{1,2,3}^{-1}.
\] (39)

1.6. Free bosonic realization of \( \mathbf{R}_{1,2,3} \)

Analogous to the continuum realization of the TE-Boltzmann weights proposed in eq.(4.1) of [17], also our (33) can be written in a bosonic realization. In this realization the cyclic weights \( W_p(n) \) of (23) are replaced by the following Gaussian weights:

\[
W_x(\sigma) = \exp \left( \frac{i}{2\hbar} \frac{x}{x - 1} \sigma^2 \right); \quad \sigma \in \mathbb{R}, \quad x \in \mathbb{C}; \quad \Im \frac{x}{x - 1} > 0.
\] (40)

At each vertex \( j \) of a graph define a pair of operators \( \mathbf{a}_j, \mathbf{p}_j \) satisfying \([\mathbf{a}_j, \mathbf{p}_j] = i\hbar \delta_{j,j'}\), and scalar variables \( u_j, w_j \). We choose a basis \( |\sigma_j\rangle \) with \( \langle \sigma_j | \cdot | \sigma_j \rangle = \delta(\sigma_j - \sigma_j') \), such that for \( \psi(\sigma) \in L^2 \) we have

\[
\psi(\sigma_j) \overset{def}{=} \langle \sigma_j | \psi \rangle; \quad \langle \sigma_j | \mathbf{a}_j | \psi \rangle = \sigma_j \psi(\sigma_j); \quad \langle \sigma_j | \mathbf{p}_j | \psi \rangle = \frac{i}{\hbar} \frac{\partial \psi(\sigma_j)}{\partial \sigma_j}.
\] (41)
For each set of vertices we define the corresponding operators and scalars and a direct product space of the single vertex spaces. Consider now the following mapping $R_{1,2,3}$ in the product space of three points $j = 1, 2, 3$ by

$$R_{123} q_j R_{123}^{-1} = \sum_{k=1}^{3} \frac{\partial \log u'_j}{\partial \log u_k} q_k + \frac{\partial \log u'_j}{\partial \log w_k} p_k \equiv q'_j$$

$$R_{123} p_j R_{123}^{-1} = \sum_{k=1}^{3} \frac{\partial \log w'_j}{\partial \log u_k} q_k + \frac{\partial \log w'_j}{\partial \log w_k} p_k \equiv p'_j. \tag{42}$$

where the relation between the primed and unprimed scalars $u_j, w_j$ is given by (13), putting there formally $N = 1$. The $\kappa_j$ are further parameters (“coupling constants”) at the vertices $j$. As the following proposition shows, equations (12) are the bosonic continuum analogs to eqs.(21) of the discrete case.

**Proposition 3** In the basis (42) the operator $R_{1,2,3}$ has the following kernel

$$\langle \sigma_1, \sigma_2, \sigma_3 | R_{1,2,3} | \sigma'_1, \sigma'_2, \sigma'_3 \rangle$$

$$= \delta(\sigma_2 - \sigma_3) \sigma_1 e^{-\frac{i}{2\hbar}\Sigma(\sigma, \sigma')} W_{x_1}(\sigma_2 - \sigma_1) W_{x_2}(\sigma_2' - \sigma_1') W_{x_3}(\sigma_2' - \sigma_1)$$

with the constraint $x_1 x_2 = x_3 x_4$. In terms of the variables $u_j, w_j, \kappa_j$, $(j = 1, 2, 3)$, the $x_k \in \mathbb{R}$ are defined by (obtained by putting formally $\omega^{-1/2} \rightarrow -1$ in (33)):

$$x_1 = -\frac{1}{\kappa_1} \frac{u_2}{u_1}; \quad x_2 = -\kappa_2 \frac{u'_2}{u'_1}; \quad x_3 = \frac{u'_2}{u_1}; \quad x_4 = \frac{\kappa_2 u_2}{\kappa_1 u'_1}, \tag{44}$$

where $u'_1$ and $u'_2$ are defined as in (77) with $N = 1$.

**Proof**: We give the proof for one of the six equations (12), as the other equations follow analogously. Let us write shorthand $|\sigma\rangle$ for $|\sigma_1, \sigma_2, \sigma_3\rangle$ and $d^3\sigma = d\sigma_1 d\sigma_2 d\sigma_3$ etc. We consider:

$$\int d^3\sigma' \langle \sigma | R_{1,2,3} | \sigma' \rangle \langle \sigma' | q_3 | \sigma'' \rangle = \int d^3\sigma' \langle \sigma | q_3 | \sigma' \rangle \langle \sigma' | R_{1,2,3} | \sigma'' \rangle \tag{45}$$

which should be satisfied for all $\sigma_1, \sigma_2, \sigma_3, \sigma'_1, \sigma'_2, \sigma'_3$. Written more explicitly, the kernel (13) is:

$$R_{\sigma_1, \sigma_2, \sigma_3} = \delta(\sigma_2 - \sigma_3 - \sigma'_2 - \sigma'_3) \exp \left( \frac{i}{2\hbar} \Sigma(\sigma, \sigma') \right);$$

where

$$\Sigma(\sigma, \sigma') = \frac{w_1(\sigma_2 - \sigma_1)^2 + u_3(\sigma_1 - \sigma'_2)^2}{u_1 w_1(\kappa_1 u_1 + u_2)} + \frac{(\kappa_1 u_1 w_2 + \kappa_3 u_2 w_3 + \kappa_1 \kappa_3 u_1 w_3)(\sigma_2 - \sigma'_1)^2}{\kappa_3 w_3(\kappa_1 u_1 + u_2)}$$

$$+ \frac{u_3(\kappa_1 u_1 w_2 + \kappa_3 u_2 w_3 + \kappa_1 \kappa_3 u_1 w_3)(\sigma'_2 - \sigma'_1)^2}{(\kappa_3 u_3 w_3 + w_1 w_2 + u_3 w_2)(\kappa_1 u_1 + u_2)} - 2(\sigma'_1 - \sigma_1)\sigma'_3. \tag{46}$$

From (12) we get:

$$q'_3 = \frac{(w_1 + u_3)u_2(q_2 - q_1) + u_2u_3q_3 + (u_2 + \kappa_1 u_1)w_1p_1}{u_2u_3 + u_2w_1 + \kappa_1 u_1 w_1}.$$
Free parameterization of the MTE

and (45) becomes:

\[
\int d^3\sigma' \delta(\sigma_2 + \sigma_3 - \sigma_2' - \sigma_3') \exp \left( \frac{i}{2\hbar} \Sigma(\sigma, \sigma') \right) \sigma_3'' \delta(\sigma' - \sigma'')
\]

\[
= \int d^3\sigma' \delta(\sigma - \sigma') \frac{(w_1 + u_3)u_2(\sigma'_2 - \sigma'_1) + u_2u_3\sigma'_3 + (u_2 + \kappa_1u_1)w_1\frac{\hbar}{\partial \sigma'_1}}{u_2u_3 + u_2w_1 + \kappa_1u_1w_1} \times
\]

\[
\times \delta(\sigma'_2 + \sigma'_3 - \sigma''_2 - \sigma''_3) \exp \left( \frac{i}{2\hbar} \Sigma(\sigma', \sigma'') \right).
\]

(47)

Since

\[
(u_2 + \kappa_1u_1)\frac{w_1}{2} \frac{\partial \Sigma(\sigma', \sigma'')}{\partial \sigma'_1} = \frac{(w_1 + u_3)u_2\sigma'_1 - u_2w_1\sigma'_2 - u_2u_3\sigma''_2 + (u_1u_2 + \kappa_1u_1w_1)\sigma''_3}
\]

eq.(47) reduces to

\[
\sigma_3'' \delta(\sigma_2 + \sigma_3 - \sigma'_2 - \sigma''_3) = \frac{u_2u_3(\sigma_2 + \sigma_3 - \sigma''_2) + (u_2w_1 + \kappa_1u_1w_1)\sigma''_3}{u_2u_3 + u_2w_1 + \kappa_1u_1w_1} \delta(\sigma_2 + \sigma_3 - \sigma'_2 - \sigma''_3)
\]

\[\square\]

2. The modified tetrahedron equation

For three-dimensional integrable spin models the Tetrahedron Equation (TE) plays a role which the Yang-Baxter equation has for two-dimensional integrable spin models. The TE provides the commutativity of so-called layer-to-layer transfer matrices. In our case, where the dynamical variables form an affine Weyl algebra, we are able to define a more general equation: the Modified Tetrahedron Equation (MTE), which provides the commutativity of more complicated transfer matrices, see e.g \[3, 6\]. In Fig. 2 we show a graphical image of the mappings leading to the tetrahedron equation (4): the sequence of mappings \(Q_1 \rightarrow Q_2 \rightarrow Q_3 \rightarrow Q_4 \rightarrow Q_5\) gives the same \(Q_5\) as \(Q_1 \rightarrow Q_8 \rightarrow Q_7 \rightarrow Q_6 \rightarrow Q_5\).

Following eq.(47) let us fix the following notation for the superposition of two mappings \(A\) and \(B\):

\[
((A \cdot B) \circ \Phi) \overset{def}{=} (A \circ (B \circ \Phi)).
\]

(48)

Due to the uniqueness of the mapping \(R\) discussed in section 1.2, p.3, we arrive at the

Proposition 4 The mapping \(R\) solves the Tetrahedron Equation:

\[
R_{123} \cdot R_{145} \cdot R_{246} \cdot R_{356} = R_{356} \cdot R_{246} \cdot R_{145} \cdot R_{123},
\]

(49)

acting in the space of the twelve affine Weyl elements \(u_1, w_1, u_2, w_2, \ldots, w_5, u_6, w_6\).

Since, as has been discussed in Sec. 1.3, any rational automorphism of the ultra-local Weyl algebra implies a rational mapping in the space of \(N\)-th powers of the parameters of the representation, its is a direct consequence of (49) that the \(R_{i,j,k}^{(f)}\) of (15) solve the tetrahedron equation with the variables \(u_j^N, w_j^N, j = 1, \ldots, 8\):

\[
R_{123}^{(f)} \cdot R_{145}^{(f)} \cdot R_{246}^{(f)} \cdot R_{356}^{(f)} = R_{356}^{(f)} \cdot R_{246}^{(f)} \cdot R_{145}^{(f)} \cdot R_{123}^{(f)}.
\]

(50)
We want to get this functional tetrahedron equation not only for the $N$-th powers of the variables but for the variables $u_j$ and $w_j$ directly. However, when taking the $N-th$ roots, not all phases of the $u_j$, $w_j$ can be chosen independently. In Sec. 3.2 we shall show explicitly how to make an independent choice of phases.

Once an appropriate choice of phases has been made, we obtain the functional tetrahedron equation on the variables $u_j$, $w_j$. Now using (39) the functional tetrahedron equation can be canceled between the two sides of (49), and we are left with the Modified Tetrahedron Equation for the finite dimensional $R$-matrices:

$$R_{1,2,3} \cdot \left( R_{1,2,3}^{(f)} \circ R_{1,4,5} \right) \cdot \left( R_{1,2,3}^{(f)} \circ R_{1,4,5} \circ R_{2,4,6} \right) \cdot \left( R_{1,2,3}^{(f)} \circ R_{1,4,5} \circ R_{2,4,6} \circ R_{3,5,6} \right) \sim R_{3,5,6} \cdot \left( R_{3,5,6}^{(f)} \circ R_{2,4,6} \right) \cdot \left( R_{3,5,6}^{(f)} \circ R_{2,4,6} \circ R_{1,4,5} \right) \cdot \left( R_{3,5,6}^{(f)} \circ R_{2,4,6} \circ R_{1,4,5} \circ R_{1,2,3} \right)$$

Observe that due to the cancellation of the functional tetrahedron equation there is no $R_{3,5,6}^{(f)}$ on the left hand side of (51) and no $R_{1,2,3}^{(f)}$ on the right hand side. Because of the
uniqueness of the mapping shown in Lemma 1 on page 7, the left and right hand sides of (51) may differ only by a scalar factor, which arises when we pass from the equivalence of the mappings to the equality of the matrices. So, in matrix element notation the MTE reads
\[
\sum_{j_1 \ldots j_6} (R^{(1)})_{j_1j_2j_3}^{i_1i_2i_3} (R^{(2)})_{j_1i_4i_5}^{k_1j_4j_5} (R^{(3)})_{j_2j_4i_6}^{k_2k_4j_6} (R^{(4)})_{j_3j_5j_6}^{k_3k_5k_6} = \rho \sum_{j_1 \ldots j_6} (R^{(8)})_{j_3j_5j_6}^{i_3i_5i_6} (R^{(7)})_{j_2j_4k_6}^{i_2i_4j_6} (R^{(6)})_{i_1j_4j_5}^{i_1k_4k_5} (R^{(5)})_{j_1j_2j_3}^{k_1k_2k_3}, \tag{52}
\]
where \(R^{(1)}\) corresponds to \(R_{1,2,3}\), \(R^{(2)}\) to \(R_{1,2,3}^{(j)} \circ R_{1,4,5}\), etc. Here \(\rho\) is the scalar factor. The matrix elements of each \(R^{(j)}\) as functions of the Fermat-curve parameters \(x_i^{(j)}, y_i^{(j)}\) are given by Proposition 3 with functional mappings applied as shown in (51). The \(N^3\)-th power of the scalar factor in (52) is
\[
\rho^{N^3} = \frac{\det R^{(1)} \det R^{(2)} \det R^{(3)} \det R^{(4)}}{\det R^{(8)} \det R^{(7)} \det R^{(6)} \det R^{(5)}}, \tag{53}
\]
and this can be obtained from the determinant of one single matrix \(R_{1,2,3}\) just by substituting the respective coordinates.

If the realization of the mapping by the free bosonic weight function (13) is used, the corresponding modified tetrahedron equation involves integrations over \(\mathbb{R}\) instead of the summations over \(\mathbb{Z}_N\). The bosonic MTE may be proven directly with the help of Gaussian integrations.

### 2.1. Calculation of the determinant of \(R_{1,2,3}\)

We use the representation (33) to find a closed expression for \(\det R_{1,2,3}\). The numerator term \(W_{p_2}(j_2 - j_1)\) is diagonal, so it just contributes a factor \((\prod_n W_{p_2}(n))^{N^2}\) to the determinant. For later convenience, we treat the other numerator factor \(W_{p_1}(i_2 - i_1)\) of (33) differently: using the Fermat curve automorphism (28) we write
\[
W_{p_1}(n) = \frac{1}{W_{Op_1}(-n) \Phi(n)}.
\]
\(W_{Op_1}(i - j)\) is diagonal and its determinant is trivially calculated. We combine the factor \(\Phi(i_2 - i_1)\) with the two non-diagonal terms \(W_{p_3}, W_{p_4}\) and write:
\[
\det\langle i_1, i_2, i_3 | R_{1,2,3} | j_1, j_2, j_3 \rangle = \left(\prod_{n=0}^{N-1} \frac{W_{p_2}(n)}{W_{Op_1}(n)}\right)^{N^2} \frac{\delta_{i_2+i_3+j_2+j_4} \omega^{(j_1-i_1)j_3}}{\Phi(i_2-i_1) W_{p_3}(j_2-i_1) W_{p_4}(i_2-j_1)} \tag{54}
\]
We now calculate the determinant on the right hand side of (54) from its finite Fourier transform in the indices \(i_1\) and \(j_1\). So we define and evaluate
\[
\langle i_1, i_2, i_3 | R_{1,2,3}^{(j)} | j_1, j_2, j_3 \rangle
\]
Free parameterization of the MTE

\[
\delta_{i_2+i_3,j_2+j_3} \frac{\omega^{i_1 j_2-i_2 j_1+(j_3-i_3) j_3}}{\Phi(j_3-i_3)} \frac{1}{N} \sum_{a'} \frac{\omega^{(i_3-i_1)a'}}{\Phi(a') W_{p_4}(a')} \sum_{b'} \frac{\omega^{-(j_3-j_1)b'}}{W_{p_4}(b')}
\]

(55)

In the last line we have used the property

\[
\Phi(a + b) = \Phi(a) \Phi(b) \omega^{ab}
\]

(56)

which, supplying a factor \(\omega^{(i_2-j_2)a'}\), decouples the \(a'\)- and \(b'\)-summations in the presence of \(\delta_{i_2+i_3,j_2+j_3}\). The determinant of the first three factors of the last line of (55) will again be calculated from its Fourier transform. So we define and evaluate

\[
\langle i_1, i_2, i_3 | P | j_1, j_2, j_3 \rangle = \frac{1}{N^2} \sum_{c,d} \omega^{i_1 c-j_1 d} \delta_{i_2+i_3,j_2+j_3} \frac{\omega^{j_2 c-i_2 d+(j_3-i_3) j_3}}{\Phi(i_3) \Phi(j_3)} \omega^{i_3 j_3}
\]

(57)

so that

\[
\det \langle i_1, i_2, i_3 | P | j_1, j_2, j_3 \rangle = \det \| \delta_{i_2+i_3,j_2+j_3} \delta_{i_1,-j_2} \delta_{j_1,-i_2} \| = (-1)^{N^2(N-1)/2}.
\]

(58)

Combining (64),(65),(67) and (68), our preliminary result is:

\[
\det < i_1, i_2, i_3 | \mathbf{R}_{1,2,3} | j_1, j_2, j_3 > \]

\[
= \left( (-1)^{(N-1)/2} \prod_k \frac{W_{p_2}(k)}{W_{Op_1}(k)} \prod_m \sum_a \frac{\omega^{ma}}{\Phi(a) W_{p_4}(a)} \prod_n \sum_b \frac{\omega^{nb}}{W_{p_4}(b)} \right)^{N^2}.
\]

(59)

We may simplify this formula by introducing the function \(V(x)\) on the Fermat curve

\[
V(x) \overset{\text{def}}{=} \prod_{n=1}^{N-1} (1 - \omega^n x)^n.
\]

(60)

Writing \((V(\omega^{-1}))^2\) as product of \(N^2\) factors of the form \((1 - \omega^n)\) times powers of \(\omega\), we compute

\[
V(\omega^{-1}) = N^{N/2} e^{i \pi (N-1)(N-2)/12}.
\]

(61)

It is useful to note that

\[
\prod_n \sum_a \frac{\omega^{na}}{\Phi(a)} = V(\omega^{-1}); \quad \prod_n \Phi(n) = e^{-\pi i (N^2-1)/6}.
\]

(62)

Writing out the factors of \((x^{N(N-1)/2} V(\omega^{-1} x^{-1})) V(x)\) and extracting several powers of \(\omega\), we obtain

\[
V(\omega^{-1} x^{-1}) = \frac{y^{N(N-1)/2}}{x^{N(N-1)/2}} \frac{e^{i \pi (N-1)(N-2)/6}}{V(x)}.
\]

(63)

We can express the terms involving \(p_1\) and \(p_2\) using \(V(x)\):

\[
\prod_n W_{p_2}(n) = \frac{V(x_2)}{y_2^{(N-1)/2}}; \quad \prod_n \frac{1}{W_{Op_1}} = \frac{V(x_1)}{y_1^{(N-1)/2}} e^{-i \pi (N^2-1)/6}.
\]

In the ratio \(V(x)/V(\omega x)\) many terms cancel, leading to

\[
\frac{V(x)}{V(\omega x)} = \left( \frac{y}{1-\omega x} \right)^N.
\]

(64)
This can be used to compute the $p_3$-term in (64): We define
\[ F_{p=(x,y)} = \prod_n \sum_b \frac{\omega^n b}{W_p(b)}, \]
which, using $W_\omega(x,y)(b) = (1 - \omega x) y^{-1} W_{\omega x,y}(b + 1)$, is seen to satisfy
\[ \frac{F_\omega(x,y)}{F(x,y)} = \omega^{N(N-1)/2} \left( \frac{y}{1 - \omega x} \right)^N, \]
where $q_0$, $q_\infty$, and $q_1$ are the three special Fermat points introduced in (31). This is solved by
\[ F_{(x,y)} = (\omega x)^{N(N-1)/2} \frac{V(\omega^{-1})}{V(x)}. \]
Finally, we consider the $p_3$ term: Defining
\[ G_{p=(x,y)} = \prod_n \sum_a \frac{\omega^n a}{\Phi(a) W_p(a)}, \]
which satisfies
\[ \frac{G_\omega(x,y)}{G(x,y)} = \left( \frac{y}{1 - \omega x} \right)^N. \]
Using $G_{q_1} = 1$, $G_{q_\infty} = 0$, $G_{q_0} = V(\omega^{-1})$, we get $G_p = V(\omega^{-1})V(x)$. Inserting these results into (64), our final expression for $\det R_{1,2,3}$ is:
\[ \det R = N^{N^3} \left( \frac{x_4}{y_1 y_2} \right)^{N(N-1)/2} \frac{V(x_1) V(x_2)}{V(x_3) V(x_4)} \right)^{N^2}. \]
The relation $x_1 x_2 = \omega x_3 x_4$ has not yet been used and is still to be imposed here. For $N = 2$ eq. (65) gives
\[ \det R = 2^8 \left( \frac{x_4}{y_1 y_2} \right)^4 \left( \frac{1 - x_1}{1 - x_3} \frac{1 - x_2}{1 - x_4} \right)^4 = \left( 4 x_4 \frac{y_1 y_2}{y_3 y_4} \left( 1 + x_3 \right) \left( 1 + x_4 \right) \right)^4, \]
in agreement with (65). Observe that, despite the quite similar appearance of $W_{p_3}$ and $W_{p_4}$ in (33), different phases make (65) unsymmetrical between $x_3$ and $x_4$, compare (33).

3. Parameterization of the Fermat points

Now the most important step follows: the parameterization of the Fermat points for each of the eight $R$-matrices. Recall that $x_1^{(j)}$ is determined by the other three $x_i^{(j)}$ due to (34).

Writing repeatedly the parameterization (33),(36) for the eight $R$-matrices, then applying repeatedly the functional mappings as it is written in (31), we get for the arguments appearing in (32):
\[ x_1^{(j)} = \frac{1}{\sqrt{\omega}} \Xi_{j1}; \quad x_2^{(j)} = \frac{1}{\sqrt{\omega}} \Xi_{j2}; \quad x_3^{(j)} = \frac{1}{\omega} \Xi_{j3}; \quad x_4^{(j)} = \frac{x_1^{(j)} x_2^{(j)}}{\omega x_3^{(j)}}; \]
\[ y_{31}^{(j)} = \Upsilon_{j1}; \quad y_{41}^{(j)} = \frac{1}{\sqrt{\omega}} \Upsilon_{j2}; \quad y_{32}^{(j)} = \Upsilon_{j3}; \quad \text{where } y_{ik}^{(j)} \equiv \frac{y_{i}^{(j)}}{y_{k}^{(j)}}. \]
Here for any \( f \) it is implied that
\[
\begin{align*}
f^{(2)} &= \mathcal{R}_{1,2,3}^{(f)} \circ f^{(1)}; \quad f^{(3)} = \mathcal{R}_{1,2,3}^{(f)} \mathcal{R}_{1,4,5}^{(f)} \circ f^{(1)}; \quad f^{(4)} = \mathcal{R}_{1,2,3}^{(f)} \mathcal{R}_{1,4,5}^{(f)} \mathcal{R}_{2,5,6}^{(f)} \circ f^{(1)},
\end{align*}
\]
and
\[
\begin{align*}
f^{(5)} &= \mathcal{R}_{1,2,3}^{(f)} \mathcal{R}_{1,4,5}^{(f)} \mathcal{R}_{2,4,6}^{(f)} \mathcal{R}_{3,5,6}^{(f)} \circ f^{(1)}.
\end{align*}
\]
For the right hand side of (62) we define for any \( f \)
\[
\begin{align*}
f^{(8)} &= \mathcal{R}_{3,5,6}^{(f)} \circ f^{(1)}; \quad f^{(7)} = \mathcal{R}_{3,5,6}^{(f)} \mathcal{R}_{2,4,6}^{(f)} \circ f^{(1)}; \quad f^{(6)} = \mathcal{R}_{3,5,6}^{(f)} \mathcal{R}_{2,4,6}^{(f)} \mathcal{R}_{1,4,5}^{(f)} \circ f^{(1)}.
\end{align*}
\]
Due to the validity of the functional tetrahedron equation the four times transformed function \( f^{(5)} = \mathcal{R}_{3,5,6}^{(f)} \mathcal{R}_{2,4,6}^{(f)} \mathcal{R}_{1,4,5}^{(f)} \mathcal{R}_{1,2,3}^{(f)} \circ f^{(1)} \) coincides with (63).

Observe that e.g.
\[
\begin{align*}
u_1^{(3)} &= u_1^{(4)} = u_1^{(5)}; \quad u_2^{(2)} = u_2^{(3)}; \quad u_2^{(4)} = u_2^{(5)}; \quad u_3^{(2)} = u_3^{(3)} = u_3^{(4)}; \quad u_4^{(2)} = u_4^{(3)} = u_4^{(4)}; \quad u_5^{(2)} = u_5^{(3)} = u_5^{(4)}; \quad u_5^{(8)} = u_5^{(1)} = u_5^{(2)} = u_5^{(3)}.
\end{align*}
\]
The MTE’s leave the following four “centers” invariant, i.e. for \( j = 1, \ldots, 8 \) we have:
\[
\begin{align*}
\mathcal{C}_1 &= u_4^{(j)} u_5^{(j)} u_6^{(j)}; \quad \mathcal{C}_2 = \frac{u_2^{(j)} u_3^{(j)} u_4^{(j)}}{u_6^{(j)}}; \quad \mathcal{C}_3 = \frac{w_3^{(j)} w_5^{(j)} u_4^{(j)}}{u_1^{(j)}}; \quad \mathcal{C}_4 = w_1^{(j)} w_2^{(j)} w_4^{(j)}.
\end{align*}
\]
E.g. \( \mathcal{C}_1'' = \mathcal{C}_1 \) because variables with indices 4,5,6 are not transformed by \( \mathcal{R}_{1,2,3}^{(f)} \), then \( \mathcal{C}_1'' = \mathcal{C}_1 \) since \( u_4 u_5 u_6 \) is center of \( \mathcal{R}_{1,4,5}^{(f)} \) and 6 does not appear in \( \mathcal{R}_{1,4,5}^{(f)} \). \( u_5 u_6 \) is center of \( \mathcal{R}_{2,5,6}^{(f)} \) etc.

Eqs. (66), (67) provide a ”free parameterization of the MTE” which generalizes the free parameterization of the single \( \mathcal{R}_{1,2,3}^{(f)} \) introduced in remark 2, p. 3. It corresponds
Free parameterization of the MTE

Figure 3. Parameterization of the arguments $u^{(j)}_i$, $w^{(j)}_i$ of the rational mapping $R^{(j)}_{i,j,k}$ in terms of line-section ratios.

to the following scenario: We start with twenty-four arbitrary complex numbers $u^{(1)}_j, w^{(1)}_j, \kappa_j$, $j = 1..8$, and apply repeatedly the functional mappings $R^{(j)}$, choosing appropriately the phases of $u^{(k)}_j, w^{(k)}_j$. So we obtain a parameterization of the eight $R$-matrices obeying the MTE.

The natural question arises: how many independent parameters has the MTE as a matrix identity? As we see already from the existence of the centers (72), some of the twenty-four parameters will occur only in certain combinations.

In order to determine the independent variables in a systematic way, in the next subsection we shall use a simple constructive procedure: We express the $u_j$ and $w_j$ in terms of line section ratios, the parameterization being designed such as to automatically conserve the centers of the mapping. This is in the same spirit as the introduction of $\tau$-functions in the theory of solitons. We shall find that as a matrix identity the MTE may be parameterized by eight independent continuous parameters and eight discrete phases common for left and right hand sides of MTE, and besides each of left and right hand sides contains four extra independent discrete parameters. In particular, the couplings $\kappa_j$ can all be absorbed by a rescaling.

Note that one great advantage of the MTEs, which is not shared by Yang-Baxter equations, is that many different parameterizations can be found and can be chosen according to the particular calculations and applications one likes to do.

3.1. Parameterization in terms of line section ratios

We now parameterize the $u^{(j)}_i$, $w^{(j)}_i$ in terms of ratios of parameters which can be read off from the four line graphs (“quadrilaterals”) shown in Fig. 2. Fig. 3 gives an enlarged detail of Fig. 2 with labels attached, which are explained in the following:

In the quadrilateral $Q_1$ there are four directed lines $A$, $B$, $C$, $D$. The six vertex points
cut the lines into four sections each. We denote the sections of line $A$ by $a_0$, $a_1$, $a_2$, $a_3$ (the indices increasing in the direction of the line). Analogously, we label the sections of lines $B$, $C$, $D$ by $b_0$, $b_1$, $b_2$, $b_3$. This way for each quadrilateral $Q_j$ we have defined 16 variables.

Now, to each vertex $i$ of each quadrilateral $Q_j$ we associate a pair of variables $u_i^{(j)}$, $w_i^{(j)}$ (which determine the Fermat points in (53)), and we require these to be given in terms of the $a_0$, $a_1$, $a_2$, $a_3$ of the respective quadrilateral as follows:

For a $u_i^{(j)}$, take $Q_j$ and look from point $i$ in the direction of the arrows and select the right-pointing of the two lines. Now $u_i^{(j)}$ is the ratio of the variable attached to the section before to the variable after the vertex. For the $w_i^{(j)}$ take the left-pointing line, and divide the variable after the vertex by the variable before the vertex. So, in the expressions for the $u_i^{(j)}$ the index of the numerator is one smaller than that for the denominator, the inverse is true for the $w_i^{(j)}$.

Passing from one quadrilateral to the next one, corresponding to a mapping $\mathcal{R}$, always three of the “internal” lines are changed, and for distinction, we attach to these changed variables dashes and daggers. The eight “external” variables $a_0$, $a_3$, $d_0$, $d_3$ are never changed by our mappings. Of the eight “internal” variables (these have the indices 1 and 2) five are unchanged in each mapping. To collect these definitions, we define

$$U_j = \left[ u_1^{(j)}, u_2^{(j)}, \ldots, u_5^{(j)}, u_6^{(j)}, w_1^{(j)}, w_2^{(j)}, \ldots, w_5^{(j)}, w_6^{(j)} \right].$$

(73)

Then from Figs. 2-5 we read off, applying successively the anticlockwise mappings:

$$U_1 = \left[ \frac{c_2}{c_3}, \frac{b_2}{b_3}, \frac{b_1}{b_2}, \frac{a_2}{a_3}, \frac{a_1}{a_2}, \frac{a_0}{a_1}, \frac{d_3}{d_2}, \frac{d_2}{d_1}, \frac{c_2}{c_1}, \frac{d_1}{d_0}, \frac{c_1}{b_0}, \frac{b_1}{b_0} \right];$$

$$U_2 = \left[ \frac{c_1}{c_2}, \frac{b_1}{b_2}, \frac{b_2}{b_3}, \frac{a_2}{a_3}, \frac{a_1}{a_2}, \frac{a_0}{a_1}, \frac{d_3}{d_2}, \frac{d_2}{d_1}, \frac{c_2}{c_1}, \frac{d_1}{d_0}, \frac{c_1}{b_0}, \frac{b_1}{b_0} \right];$$

$$U_3 = \left[ \frac{c_0}{c_1}, \frac{b_1}{b_2}, \frac{b_3}{b_0}, \frac{a_1}{a_2}, \frac{a_0}{a_1}, \frac{a_0}{d_0}, \frac{d_3}{d_2}, \frac{d_2}{d_1}, \frac{c_3}{c_2}, \frac{d_1}{d_0}, \frac{c_2}{b_1}, \frac{b_1}{b_0} \right];$$

$$U_4 = \left[ \frac{c_0}{c_1}, \frac{b_1}{b_2}, \frac{b_3}{b_0}, \frac{a_1}{a_2}, \frac{a_0}{a_1}, \frac{a_0}{d_0}, \frac{d_3}{d_2}, \frac{d_2}{d_1}, \frac{c_3}{c_2}, \frac{d_1}{d_0}, \frac{c_2}{b_1}, \frac{b_1}{b_0} \right];$$

$$U_5 = \left[ \frac{c_0}{c_1}, \frac{b_1}{b_2}, \frac{b_3}{b_0}, \frac{a_1}{a_2}, \frac{a_0}{a_1}, \frac{a_0}{d_0}, \frac{d_3}{d_2}, \frac{d_2}{d_1}, \frac{c_3}{c_2}, \frac{d_1}{d_0}, \frac{c_2}{b_1}, \frac{b_1}{b_0} \right];$$

(74)

We write $a_2^T$ instead of $a_2^T$ and $d_1^T$ instead of $d_1^T$, etc. Transforming clockwise in Fig. 2, we get

$$U_8 = \left[ \frac{c_2}{c_3}, \frac{b_2}{b_3}, \frac{b_0}{b_1}, \frac{a_2}{a_3}, \frac{a_0}{a_2}, \frac{a_0}{a_1}, \frac{d_3}{d_2}, \frac{d_2}{d_1}, \frac{c_1}{c_0}, \frac{d_0}{d_1}, \frac{c_0}{b_1}, \frac{b_1}{b_0} \right];$$

$$U_7 = \left[ \frac{c_2}{c_3}, \frac{b_1}{b_2}, \frac{b_1}{b_2}, \frac{a_1}{a_2}, \frac{a_0}{a_1}, \frac{a_0}{a_1}, \frac{d_3}{d_2}, \frac{d_2}{d_1}, \frac{c_1}{c_0}, \frac{d_0}{d_1}, \frac{c_0}{b_1}, \frac{b_1}{b_2} \right];$$

$$U_7 = \left[ \frac{c_2}{c_3}, \frac{b_1}{b_2}, \frac{b_1}{b_2}, \frac{a_1}{a_2}, \frac{a_0}{a_1}, \frac{a_0}{a_1}, \frac{d_3}{d_2}, \frac{d_2}{d_1}, \frac{c_1}{c_0}, \frac{d_0}{d_1}, \frac{c_0}{b_1}, \frac{b_1}{b_2} \right];$$

(74)
etc. Transforming clockwise two times more, we arrive at an alternative expression for \(U_5\), which for distinction we call \(U_5'\):
\[
U_5' = \begin{bmatrix}
c_0 & b_0 & b_1 & a_0 & a_1 & a_2 & d_1 & d_2 & c_2 & c_3 & b_3 \\
\frac{1}{c_1} & b_1' & b_2' & a_1' & a_2' & a_3' & d_1' & d_2' & c_1' & c_2' & b_2'
\end{bmatrix}.
\]
(75)

We see that this particular parameterization in terms of ratios automatically incorporates the invariance of the centers of the mappings. E.g. for \(R^{(1)}\) (in our notation \(u_{(3)}^{'(2)}\) is the \(u_j'\) of \((73)\)):
\[
u_{(3)}^{'(2)} = u_{(3)}^{(1)}; \quad \frac{u_{(3)}^{'(2)}}{w_{(3)}^{'(2)}} = \frac{u_{(3)}^{(1)}}{w_{(3)}^{(1)}}; \quad w_{(3)}^{'(2)} = w_{(3)}^{(1)} w_{(1)}^{(2)}.
\]

Also more complicated conditions are fulfilled automatically, e.g.
\[
u_{(4)}^{(1)} w_{(3)}^{(1)} w_{(1)}^{(1)} = u_{(1)}^{(1)} w_{(2)}^{(1)} w_{(3)}^{(1)}.
\]

Observe that because in the mapping from \(Q_1\) to \(Q_2\) the line \(A\) keeps the same intersection points, there is no \(a_i'\) in the formulae for the \(U_j\), similarly, there are no \(b_i', c_i', d_i', a_i, b_i, c_i, d_i\). So, altogether, there are 24 primed or dagged variables appearing. However, some coincide as we will see. From \((13)\) and \((14)\) we easily obtain the following relations, which allow to express their \(N\)-th powers recursively in terms of the \(N\)-th powers of the unprimed variables:
\[
b_{2}^{\mu N} a_{2}^{N} = b_{1}^{N} c_{1}^{N} d_{2}^{N} + b_{2}^{N} c_{3}^{N} d_{3}^{N} + \kappa_{1} b_{3}^{N} c_{2}^{N} \delta_{3}^{N};
\]
\[
kappa_{2}^{N} b_{1}^{N} c_{1}^{N} d_{2}^{N} = b_{1}^{N} c_{1}^{N} b_{2}^{N} + b_{3}^{N} c_{1}^{N} d_{2}^{N} + \kappa_{1} b_{3}^{N} c_{3}^{N} d_{2}^{N};
\]
\[
b_{2}^{N} c_{2}^{N} d_{2}^{N} = b_{2}^{N} c_{1}^{N} d_{1}^{N} + b_{1}^{N} c_{1}^{N} d_{1}^{N} + \kappa_{3} b_{1}^{N} c_{1}^{N} d_{1}^{N};
\]
\[
a_{2}^{N} c_{1}^{N} d_{1}^{N} = a_{1}^{N} c_{1}^{N} d_{1}^{N} + a_{2}^{N} c_{2}^{N} d_{1}^{N} + \kappa_{1} a_{3}^{N} c_{1}^{N} d_{1}^{N};
\]
\[
kappa_{4}^{N} a_{2}^{N} c_{2}^{N} d_{1}^{N} = a_{1}^{N} c_{1}^{N} d_{1}^{N} + a_{2}^{N} c_{2}^{N} d_{1}^{N} + \kappa_{3} b_{1}^{N} c_{1}^{N} d_{1}^{N};
\]
\[
a_{2}^{N} c_{1}^{N} d_{2}^{N} = a_{1}^{N} c_{1}^{N} d_{2}^{N} + a_{2}^{N} c_{2}^{N} d_{1}^{N} + \kappa_{1} a_{3}^{N} c_{1}^{N} d_{1}^{N};
\]
\[
kappa_{4}^{N} b_{1}^{N} d_{2}^{N} = a_{0}^{N} b_{1}^{N} d_{2}^{N} + a_{2}^{N} b_{3}^{N} d_{1}^{N} + \kappa_{1} b_{3}^{N} b_{3}^{N} d_{2}^{N};
\]
\[
kappa_{4}^{N} b_{1}^{N} d_{1}^{N} = a_{0}^{N} b_{1}^{N} d_{1}^{N} + a_{2}^{N} b_{3}^{N} d_{1}^{N} + \kappa_{1} b_{3}^{N} b_{3}^{N} d_{1}^{N};
\]
\[
e_{1}^{N} c_{1}^{N} d_{1}^{N} = a_{0}^{N} c_{1}^{N} d_{1}^{N} + a_{1}^{N} c_{1}^{N} d_{1}^{N} + \kappa_{3} a_{1}^{N} c_{1}^{N} d_{1}^{N};
\]
\[
\cdots
\]
Using these relations one verifies by straightforward substitution in (74) and (75) that $U_5 = U_5^\dagger \kappa$, (77) i.e. that the functional tetrahedron equations are satisfied. Eq. (77) tells us that there are eight direct relations between the dashed and dagged variables, e.g. $c_0'' = c_1''$, etc. so that in fact due to the functional tetrahedron equations the last eight equations of (76) are superfluous. This will be important for the discussion of the freedom of phase choices when taking $N$th roots.

Written in terms of our parameters $a_i$, $b_i$, etc. the arguments of the $R^{(j)}$ ($j = 1, \ldots, 8$), see (69), are

\[ x_1^{(j)} = \frac{1}{\sqrt{\omega}} X_{j1}; \quad x_2^{(j)} = \frac{1}{\sqrt{\omega}} X_{j2}; \quad x_3^{(j)} = \frac{1}{\omega} X_{j3}; \quad x_4^{(j)} = \frac{x_1^{(j)} x_2^{(j)} x_3^{(j)}}{\omega x_3^{(j)}}, \]
\[ y_{j1}^{(j)} = Y_{j1}; \quad y_{j2}^{(j)} = \frac{1}{\sqrt{\omega}} Y_{j2}; \quad y_{j3}^{(j)} = Y_{j3}, \]

where (again we do not write out $x_4^{(j)}$)

\[ X_{jk} = \begin{pmatrix} b_{2c_3} & \kappa_2 b_1 c_2 & b_1 c_3 \\ \kappa_1 b_2 c_2 & a_2 c_1 & a_1 c_2 \\ a_1 b_2 c_1 & a_1 b_2 c_1 & a_1 b_2 c_1 \end{pmatrix}; \quad Y_{jk} = \begin{pmatrix} \kappa_1 d_2 b_3 & \kappa_2 d_2 c_1 & \kappa_3 d_2 c_1 \\ d_2 b_3 & d_2 c_1 & d_2 c_1 \\ \kappa_3 d_2 c_1 & \kappa_3 d_2 c_1 & \kappa_3 d_2 c_1 \end{pmatrix}. \]

To check the validity of all the Fermat relations $x_i^{(j)N} + y_i^{(j)N} = 1$ requires using the transformation equations (74). The relations (76) involve the $N$th powers of the
variables, so to use them to get the Fermat coordinates, we have to take \( N \)-th roots, which entails discrete phase choices. The centers (72) are just ratios of the external variables:

\[
\mathbf{c}_1 = \frac{a_0}{a_3}; \quad \mathbf{c}_2 = \frac{b_0}{b_3}; \quad \mathbf{c}_3 = \frac{c_3}{c_0}; \quad \mathbf{c}_4 = \frac{d_3}{d_0}.
\] (80)

The external variables \( a_0, a_3, \ldots, d_0, d_3 \) are irrelevant and serve mainly to express all quantities in terms of ratios. We may choose them simply all to be unity. The "coupling constants" \( \kappa_j \) may all be eliminated by re-scaling the eight relevant variables \( a_1, a_2, \ldots, d_1, d_2 \) as follows:

\[
a_1 = \frac{\kappa_1 \kappa_2}{\kappa_5 \kappa_6} a_1; \quad a_2 = \frac{\kappa_1 \kappa_6}{\kappa_3} a_2; \quad b_1 = \frac{\kappa_1}{\kappa_3} b_1; \quad b_2 = \frac{\kappa_1 \kappa_6}{\kappa_2} b_2; \\
c_1 = \frac{\kappa_1 \kappa_6}{\kappa_3} c_1; \quad c_2 = \frac{\kappa_1 \kappa_6}{\kappa_2} c_2; \quad d_1 = \frac{\kappa_1 \kappa_6}{\kappa_3} d_1; \quad d_2 = \frac{\kappa_1 \kappa_6}{\kappa_2} d_2.
\] (81)

This entails a corresponding re-scaling of the dashed and daggered variables, e.g.

\[
b_2' = \frac{\kappa_1 \kappa_2}{\kappa_5 \kappa_6} b_1'; \quad c_2' = \frac{\kappa_1}{\kappa_5 \kappa_6} c_1'; \quad d_2' = \frac{\kappa_1 \kappa_2}{\kappa_5} d_1'; \quad a_2' = \frac{\kappa_1 \kappa_2}{\kappa_5 \kappa_6} a_2'; \\
c_1'' = \frac{\kappa_3}{\kappa_4 \kappa_6} c_1''; \quad d_1'' = \frac{\kappa_3 \kappa_5}{\kappa_1} d_1''; \quad a_1'' = \frac{\kappa_3 \kappa_5}{\kappa_6} a_1''; \quad b_1'' = \frac{\kappa_3}{\kappa_1} b_1''; \\
d_2'' = \frac{\kappa_3 \kappa_5}{\kappa_1} d_2''; \quad a_1' = \frac{\kappa_3 \kappa_5}{\kappa_1} a_1'; \quad b_1' = \frac{\kappa_3 \kappa_5}{\kappa_1} b_1'; \quad c_1' = \frac{\kappa_3 \kappa_5}{\kappa_1} c_1'; \quad ... 
\] (82)

So we can simplify eqs.(73) and (74) by taking \( a_0 = a_3 = b_0 = \ldots = d_3 = 1 \) and \( \kappa_1 = \kappa_2 = \ldots = \kappa_6 = 1 \) and replacing the relevant variables by their overlined counterparts.

3.2. The choice of discrete phases.

As we already mentioned, apart from the eight continuous parameters just discussed, the left hand and right hand sides of the MTE depend on phases choices arising from taking \( N \)-th roots. We investigate how many independent choices can be made and whether these affect the MTEs.

From (77) and (74), (75) we see that the left hand side (LHS) and right hand side (RHS) of the MTE have 8 arbitrary common phases of

\[
a_2^T = a_2^{\uparrow \uparrow}, \quad b_2^T = b_2^{\uparrow \uparrow}, \quad c_2^T = c_2^{\uparrow \uparrow}, \quad d_2^T = d_2^{\uparrow \uparrow}, \quad a_1'' = a_1^{\uparrow \uparrow}, \quad b_1'' = b_1', \quad c_1'' = c_1', \quad d_1'' = d_1'.
\]

These phases correspond to the phases of \( u_1^{(5)} \) etc. Furthermore, the LHS of the MTE contains 4 internal phases of

\[
c_2', \quad b_2', \quad d_2', \quad a_2''
\]

while the RHS contains 4 internal phases of

\[
a_1^\dagger, \quad c_1^\dagger, \quad b_1^\dagger, \quad d_1^\dagger.
\]

In which way does the LHS depend on its internal phases? Consider e.g. the shift

\[
c_2' \mapsto q^{-1} c_2'.
\]
According to (79) this shift changes the following Fermat coordinates:

\[ \begin{align*}
x_2^{(1)} &\mapsto q^{-1}x_2^{(1)}, \\
x_4^{(1)} &\mapsto q^{-1}x_4^{(1)}, \\
x_1^{(2)} &\mapsto q^{-1}x_1^{(2)}, \\
x_3^{(2)} &\mapsto q^{-1}x_3^{(2)}, \\
y_1^{(4)} &\mapsto qy_1^{(4)}. 
\end{align*} \]

Now note that for \( q = \omega \)

\[ W_{(q^{-1}x,y)}(n) = \frac{y}{1-x} W_{(x,y)}(n-1); \quad W_{(x,qy)}(n) = q^n W_{(x,y)}(n). \]

Therefore our shift produces

\[ \begin{align*}
\langle i_1, i_2, i_3 | R^{(1)} | j_1, j_2, j_3 \rangle &\mapsto \frac{y_2^{(1)}}{y_4^{(1)}} \frac{1-x_4^{(1)}}{1-x_2^{(1)}} \langle i_1, i_2, i_3 | R^{(1)} | j_1 + 1, j_2, j_3 \rangle q^{-j_3}, \\
\langle j_1, i_4, i_5 | R^{(2)} | k_1, j_4, j_5 \rangle &\mapsto \frac{y_3^{(2)}}{y_2^{(2)}} \frac{1-x_3^{(2)}}{1-x_1^{(2)}} \langle j_1 + 1, i_4, i_5 | R^{(2)} | k_1, j_4, j_5 \rangle q^{j_3}, \\
\langle j_3, j_5, j_6 | R^{(4)} | k_3, k_5, k_6 \rangle &\mapsto q^{j_3-j_5} \langle j_3, j_5, j_6 | R^{(4)} | k_3, k_5, k_6 \rangle.
\end{align*} \]

We see that the change considered produces a simple scalar factor and does not change the matrix structure of the LHS of the MTE:

\[ LHS(q^{-1}c_2') = \frac{y_2^{(1)}}{y_4^{(1)}} \frac{1-x_4^{(1)}}{1-x_2^{(1)}} \frac{y_3^{(2)}}{y_2^{(2)}} \frac{1-x_3^{(2)}}{1-x_1^{(2)}} LHS(c_2'). \]

In this way we may convince ourselves:

- A change of the phases of any of the eight internal variables produces only extra scalar factors for the LHS or RHS of the MTE, while the external matrix structure does not change.
- A change of the phases for any of the eight external variables produces extra scalar factors both for the LHS and RHS of the MTE, and besides it produces a change of the external matrix structure: a shift of the indices \( i_1, ..., k_6 \) and some multipliers \( q^{ \pm i_1}, ..., q^{ \pm k_6} \). However, this change is the same for the LHS and RHS of the MTE.

4. Explicit form of the MTE for \( N = 2 \)

For \( N = 2 \), using combined indices \( i = 1 + i_1 + 2i_2 + 4i_3; \ k = 1 + k_1 + 2k_2 + 4k_3 \), we can give \( (R_{i1}^{kl})^{k_1,k_2,k_3} \) explicitly in a simple matrix form: We define

\[ \begin{align*}
Y_k &= \frac{y_k}{1 + x_k} = \sqrt{\frac{1-x_k}{1+x_k}} \quad \text{for} \quad k = 1, 2, 3, 4; \\
Z_{ik} &= \frac{Y_i}{Y_k} \quad \text{for} \quad ik = 13, 14, 23, 24; \quad Z_{12} = Y_1 Y_2; \quad Z_{34} = \frac{1}{Y_3 Y_4}. 
\end{align*} \]
and get

$$R^k_i = \begin{pmatrix}
1 & Z_{24} & 0 & 0 & 0 & 0 & Z_{23} & -Z_{34} \\
Z_{13} & Z_{13}Z_{24} & 0 & 0 & 0 & 0 & -Z_{12} & Z_{14} \\
0 & Z_{13}Z_{24} & Z_{13} & Z_{14} & -Z_{12} & 0 & 0 & 0 \\
0 & 0 & Z_{14} & 1 & -Z_{34} & Z_{23} & 0 & 0 \\
0 & 0 & Z_{23} & Z_{34} & 1 & -Z_{24} & 0 & 0 \\
0 & 0 & Z_{12} & Z_{14} & -Z_{13} & Z_{13}Z_{24} & 0 & 0 \\
Z_{14} & Z_{12} & 0 & 0 & 0 & 0 & Z_{13}Z_{24} & -Z_{13} \\
Z_{34} & Z_{23} & 0 & 0 & 0 & 0 & -Z_{24} & 1
\end{pmatrix}$$

The determinant can be calculated directly:

$$\text{det } R = \left( Y_1 Y_2 \frac{(Y_3^2 + 1)(Y_4^2 - 1)}{Y_3^2 Y_4^2} \right)^4.$$  \hspace{1cm} (85)

For \( N = 2 \) we can also write the MTE quite explicitly. We shall write eq. (52) shorthand as

$$\Theta^{k_1, k_2, k_3, k_4, k_5, k_6}_{i_1, i_2, i_3, i_4, i_5, i_6} = \rho \Theta^{k_1, k_2, k_3, k_4, k_5, k_6}_{i_1, i_2, i_3, i_4, i_5, i_6}.$$  \hspace{1cm} (86)

where in obvious correspondence \( \Theta \) and \( \Theta \) are defined to be the left- and right-hand sums of products of four \( R \)-matrices. We use (83) and abbreviate \( Y_i^{(j)} \) by \( Y_{ij} \), where \( i \) labels the four points on the Fermat curve \( x_1, x_2, x_3, x_4 = x_1x_2/(\omega x_3) \), and \( j = 1, \ldots, 8 \) denote the eight arguments of the \( R^{(j)} \). The left hand side of (86) is, using (83):

$$\Theta^{k_1, k_2, k_3, k_4, k_5, k_6}_{i_1, i_2, i_3, i_4, i_5, i_6} = (-1)^{k_3 k_6} Y_1^{i_2+i_1} Y_2^{k_4+k_2} Y_3^{k_5+k_3} Y_4^{i_4+k_1} \times$$

$$\sum_{j_1, j_2, j_3, j_4, j_5, j_6} \delta_{i_2+i_5, j_2+j_3} \delta_{i_4+i_6, j_4+j_5} \delta_{j_4+j_6, k_4+k_6} \times$$

$$\left( -1 \right)^{j_1(j_3-j_5)+j_6(k_2-j_2)-j_3(j_1+k_6)+k_1 j_2} Y_1^{j_2+j_1} Y_2^{i_4+j_1} Y_3^{j_4+j_2} Y_4^{k_5+j_3} Y_5^{k_4+j_2} Y_6^{i_6+j_5} Y_7^{j_5+j_3} Y_8^{j_6+i_6},$$

where all exponents are understood modulo 2, i.e. being just 0 or 1. We can use three of the \( \delta \)'s to eliminate the sums over e.g. \( j_2, j_4, j_6 \). Then the last \( \delta \) gives a compatibility condition with the result that if \( i_4 + i_5 + i_6 + k_4 + k_5 + k_6 \) is odd, the component of \( \Theta \) vanishes and these components of the MTE are trivial. These are half of the \( 2^{12} \) components. We also see that, if these occur at all, \( Y_{11}, Y_{23}, Y_{24} \) and \( Y_{42} \) will factorize (\( Y_{11} \) appears if \( i_1 + i_2 \) is odd, etc.). Each non-zero component has a sum over eight terms on each side. The result is:

$$\Theta^{k_1, k_2, k_3, k_4, k_5, k_6}_{i_1, i_2, i_3, i_4, i_5, i_6} = \delta_{i_4+i_5+i_6, k_4+k_5+k_6} \left( -1 \right)^{i_1+i_4+i_6} Y_1^{i_2+i_1} Y_2^{k_4+k_2} Y_3^{k_5+k_3} Y_4^{i_4+k_1} \times$$

$$\sum_{j_1, j_2, j_4} \left( -1 \right)^{\beta} Y_2^{j_2+j_1} Y_3^{i_4+j_1} Y_4^{j_4+j_2} Y_5^{k_5+j_3} Y_6^{k_4+j_2} Y_7^{i_6+j_5} Y_8^{j_5+j_3},$$

$$\text{det } R = \left( Y_1 Y_2 \frac{(Y_3^2 + 1)(Y_4^2 - 1)}{Y_3^2 Y_4^2} \right)^4.$$  \hspace{1cm} (87)
where \( \tau = i_2 + i_3 + i_4 + i_5 \) and
\[
\begin{align*}
\beta &= j_1 j_2 + j_2 j_4 + j_4 j_1 + j_1 \tau + j_2 (i_1 + i_6 + k_4 + k_6) + j_4 (k_1 + k_2), \\
\gamma &= k_1 (i_4 + i_5) + k_2 (i_6 + k_4) + (i_2 + i_3) (i_1 + k_6) + k_3 k_6.
\end{align*}
\]

The analogous expression for the right hand side is:
\[
\Theta^{k_1 k_2 k_3 k_4 k_5 k_6}_{i_1 i_2 i_3 i_4 i_5 i_6} = \delta_{i_4 + i_5 + i_6, k_4 + k_5 + k_6} (-1)^\tau \frac{Y_{25}^{k_2 + k_1} Y_{18}^{i_5 + i_6} Y_{17}^{i_4 + i_2}}{Y_{36}^{k_4 + i_1}} \times
\]
\[
\sum_{j_1, j_2, j_4} (-1)^\bar{\tau} Y_{16}^{j_4 + i_1} Y_{15}^{j_4 + j_1} Y_{26}^{j_1 + k_4} Y_{27}^{j_1 + j_2} Y_{28}^{j_4 + j_2 + \tau} \times
\]
\[
Y_{38}^{j_4 + i_4 + k_4 + k_5 + k_6} Y_{48}^{j_5 + j_2 + k_2 + k_3} Y_{37}^{j_1 + j_2} Y_{47}^{j_1 + j_2} Y_{35}^{j_4 + j_2 + k_1 + k_2} Y_{45}^{k_1 + j_2},
\]
(88)

with \( \bar{\tau} = k_2 + k_3 + k_4 + k_5 \), and
\[
\bar{\beta} = j_1 (k_4 + k_5) + j_2 (j_4 + i_4) + j_4 (k_2 + k_3 + i_3),
\]
\[
\bar{\gamma} = i_1 k_5 + i_2 k_6 + k_1 k_3 + (i_4 + k_6) (k_2 + k_3 + i_3).
\]

and again all exponents are understood \textit{mod} 2.

We give two examples of non-trivial components of the MTEs: First we consider the component
\[
\Theta^{0,0,0,0,0,0}_{0,0,0,0,0,0} = \rho \Theta^{0,0,0,0,0,0}_{0,0,0,0,0,0}
\]
This is, written more explicitly, using the abbreviations of (83) adding the index \( j \):
\[
Z_{ik,j} = Y_i^{(j)} / Y_k^{(j)} \text{ for } ik = 13, 14, 23, 24, \ Z_{12,j} = Y_1^{(j)} Y_2^{(j)}, \ Z_{34,j} = 1 / (Y_3^{(j)} Y_4^{(j)}):
\]
\[
1 + Z_{24,1} Z_{13,2} + (Z_{23,1} - Z_{34,1} Z_{13,2}) Z_{13,3} Z_{13,4}
\]
\[
+ (Z_{23,2} - Z_{12,2} Z_{24,1}) Z_{14,3} Z_{14,4} - (Z_{23,1} Z_{23,2} + Z_{34,1} Z_{12,2}) Z_{34,3} Z_{34,4}
\]
\[
= \rho \left\{ 1 + Z_{24,1} Z_{13,3} + (Z_{14,5} + Z_{24,6} Z_{34,5}) Z_{24,8} Z_{24,7}
\]
\[
+ (Z_{14,6} + Z_{12,6} Z_{13,5}) Z_{23,8} Z_{23,7} - (Z_{14,6} Z_{14,5} + Z_{12,6} Z_{34,5}) Z_{34,6} Z_{34,7} \right\}.
\]
(89)

Another component:
\[
\Theta^{0,0,1,1,0,0}_{0,0,1,1,0,0} = \rho \Theta^{0,0,1,1,0,0}_{0,0,1,1,0,0}
\]
reads analogously:
\[
(1 + Z_{24,1} Z_{13,3}) Z_{23,3} Z_{23,4} \quad - (Z_{23,1} - Z_{13,2} Z_{34,1}) Z_{12,3} Z_{12,4}
\]
\[
+ (Z_{23,2} - Z_{24,1} Z_{12,2}) Z_{13,3} Z_{24,3} Z_{13,4} Z_{24,4}
\]
\[
+ (Z_{23,1} Z_{23,2} + Z_{34,1} Z_{12,2}) Z_{24,3} Z_{24,4}
\]
\[
= \rho \left\{ Z_{24,6} - Z_{24,6} Z_{13,3} + (Z_{24,6} Z_{14,5} - Z_{24,6} Z_{34,5}) Z_{24,8} Z_{24,7}
\]
\[
+ (Z_{24,6} - Z_{13,5}) Z_{13,6} Z_{23,8} Z_{23,7} + (Z_{34,5} Z_{13,6} - Z_{13,6} Z_{24,6} Z_{14,5}) Z_{34,6} Z_{34,7} \right\}.
\]
(90)

Each equation appears \textit{eight} times for different components. In order to write the symmetries compactly, we introduce the following three mappings \( a, b, c \) of the upper or lower indices:
\[
a(i_1, i_2, i_3, i_4, i_5, i_6) = (i_1 + 1, i_2 + 1, i_3, i_4 + 1, i_5, i_6);
\]
\[
b(i_1, i_2, i_3, i_4, i_5, i_6) = (i_1, i_2, i_3 + 1, i_4, i_5 + 1, i_6);
\]
\[
c(i_1, i_2, i_3, i_4, i_5, i_6) = (i_1, i_2, i_3, i_4, i_5, i_6 + 1);
\]

and
\[
ab(i_1, i_2, i_3, i_4, i_5, i_6) = a(b(i_1, i_2, i_3, i_4, i_5, i_6)), \quad \text{etc.}
\]
(91)
the same also for the $k_j$ instead of the $i_j$. Of course, the indices are always taken mod 2. Altogether, for $N = 2$ there are $2^8$ different nontrivial components, an independent set is (the same for the $\Theta$)

\[
\Theta^{k_1, k_2, k_3, 0, 0, 0}_{i_1, i_2, i_3, 0, 0} ; \quad \Theta^{k_1, k_2, k_3, 1, 1, 0}_{i_1, i_2, i_3, 0, 0} ; \quad \Theta^{k_1, k_2, k_3, 1, 0, 1}_{i_1, i_2, i_3, 0, 0} ; \quad \Theta^{k_1, k_2, k_3, 0, 1, 1}_{i_1, i_2, i_3, 0, 0}
\]

for \( i_1, i_2, i_3, k_1, k_2, k_3 = 0, 1 \). \hspace{1cm} (92)

**Proposition 5** For $N = 2$ the components of the left-hand side of the Modified Tetrahedron Equation satisfy the following symmetry relations:

\[
\Theta^{k_1, k_2, k_3, k_4, k_5, k_6}_{i_1, i_2, i_3, 0, 0, 0} = \Theta^{a(k_1, k_2, k_3, k_4, k_5, k_6)}_{a(i_1, i_2, i_3, 0, 0, 0)}
\]

\[
= (-1)^{i_1 + 1} \Theta^{b(k_1, k_2, k_3, k_4, k_5, k_6)}_{b(i_1, i_2, i_3, 0, 0, 0)} = (-1)^{i_1 + k_1} \Theta^{ab(k_1, k_2, k_3, k_4, k_5, k_6)}_{ab(i_1, i_2, i_3, 0, 0, 0)}
\]

\[
= (-1)^{i_2 + i_3 + k_2 + k_3} \Theta^{c(k_1, k_2, k_3, k_4, k_5, k_6)}_{c(i_1, i_2, i_3, 0, 0, 0)} = (-1)^{i_2 + i_3 + k_2 + k_3} \Theta^{ac(k_1, k_2, k_3, k_4, k_5, k_6)}_{ac(i_1, i_2, i_3, 0, 0, 0)}
\]

\[
= (-1)^{i_1 + i_2 + i_3 + k_1 + k_2 + k_3} \Theta^{bc(k_1, k_2, k_3, k_4, k_5, k_6)}_{bc(i_1, i_2, i_3, 0, 0, 0)} = (-1)^{i_1 + i_2 + i_3 + k_1 + k_2 + k_3} \Theta^{abc(k_1, k_2, k_3, k_4, k_5, k_6)}_{abc(i_1, i_2, i_3, 0, 0, 0)}
\]

\hspace{1cm} (93)

where \( i_1, i_2, i_3, k_1, k_2, \ldots, k_5, k_6 = 0, 1 \). Here the mappings $a$, $b$, $c$ are defined as in (74). The same equations are valid for the right-hand components, i.e. for $\Theta$ replaced by $\bar{\Theta}$.

For $k_4 + k_5 + k_6$ odd, these equations are trivial.

**Proof:** Use the explicit formulae (87) and (88). For the relations involving the mapping $a$ we shift the summation indices $j_1$, $j_2$, $j_4$. Then all exponents of the $Y$–factors are unchanged. No phase is appearing, since the shift in $\gamma$ ($\overline{\gamma}$) is compensated by the shift in $\beta$ ($\overline{\beta}$). For the relations involving the mappings $b$ and/or $c$, also all exponents of the $Y$ are unchanged. The phase factors appear from the shifts in $\gamma$ or $\overline{\gamma}$. \hspace{1cm} \Box

The terms

\[
Z_{ik,j} = y_{ik}^{(j)} \frac{1 + x_k^{(j)}}{1 + x_i^{(j)}}, \quad ik = 13, 14, 23, 24;
\]

\[
Z_{12,j} = \frac{y_{13}^{(j)} y_{23}^{(j)} (1 - x_3^{(j)})^2}{(1 + x_1^{(j)})(1 + x_2^{(j)})}; \quad Z_{34,j} = \frac{(1 + x_3^{(j)})(1 + x_4^{(j)})}{y_{31}^{(j)} y_{41}^{(j)} (1 - x_1^{(j)})^2},
\]

which appear in (89) and (90) have the following explicit form, taking all boundary coefficients and all $\kappa_j$ to be unity, compare (81), (82):

\[
Z_{13,1} = \frac{(b_2' c_2 - b_1') d_2^2}{c_2 - ib_2}; \quad Z_{14,1} = \frac{(b_2 c_2' - c_1) d_2}{(b_2 + ic_2) d_1};
\]

\[
Z_{23,1} = \frac{(b_2' c_2 - b_1') d_2^2}{c_1 b_2 - ib_1 c_2^2}; \quad Z_{24,1} = \frac{(b_2 c_2' - c_1) d_2^2}{(b_1 c_2' + ib_2 c_1) d_1};
\]

\[
\ldots Z_{23,4} = \frac{(a_2'^{m} b_2' - a_1^{m}) c_2^{m}}{b_1^{m} a_2'^{m} - ia_1^{m} b_2'^{m}}; \quad Z_{24,4} = \frac{(a_2'^{m} b_2' - b_1'^{m}) c_2^{m}}{(a_1^{m} b_2'^{m} + ia_2^{m} b_1'^{m}) c_1^{m}};
\]

(94)
etc. Discrete sign choices of square roots come in when expressing the transformed variables e.g. $b_2^\prime$, $a''_2$, etc. in terms of the original eight variables $a_1$, $a_2$, $\ldots$, $d_2$ via (76). E.g. from the first lines of (76):

\[
\begin{align*}
    b_2^\prime &= \pm \frac{1}{c_2d_2} \sqrt{b_1^2d_2^2 + b_2 + c_2^2} ; \\
    c_2 &= \pm \frac{1}{b_2d_2} \sqrt{c_1^2d_2^2 + (b_2^2 + c_2^2)d_1^2} ; \\
    d_2^\prime &= \pm \frac{1}{b_2c_2} \sqrt{(b_2^2 + b_1^2d_2^2)c_1^2 + b_1^2c_2^2d_1^2} ; \\
    a''_2 &= \pm \frac{1}{c_1d_1} \sqrt{(a_1^2d_1^2 + a_2^2d_2^2)c_2^2 + c_1^2d_2^2}.
\end{align*}
\]

All dashed or daggered variables are square roots of rational expressions.

From (85) the factor $\rho$ is:

\[
\rho = \sqrt{\prod_{i=1}^{4} Z_{12,i} (1 + Z_{34,i}(Z_{13,i}Z_{14,i}^{-1} - Z_{14,i}Z_{13,i}^{-1})) - Z_{2}^{2}}.
\]

Using the components like (90) and inserting there (95) and (94), (76) we get the MTE in terms of our eight parameters $a_1$, $a_2$, $\ldots$, $d_2$ and sixteen choices of the signs of $b_2^\prime$, $c_2$, $d_2^\prime$, $a''_2$, $c''_2$, $d''_2$, $b''_1$, $d''_2$, $a'_1$, $b'_1$, $c'_1$, $a''_2$, $b''_2$, $d''_2$, $a''_2$, $c''_2$.

We have confirmed the $N = 2$-MTE numerically for all 256 different components, choosing random complex numbers for the eight continuous variables and random signs for the sixteen square roots in the variables (96).

We conclude mentioning that for $N = 3$ we find that of the $3^{12}$ components of the MTE for $(R^{(i)}_{j,j_2,j_3})_{i_1,i_2,i_3}$ given in (33), $2 \times 3^{11}$ components are just $0 = 0$, while $3^{11}$ (not all distinct) equations have non-trivial left- and right-hand sides.

5. Conclusions

In this paper we study the Modified Tetrahedron Equation (72) in which the Boltzmann weights $R^{j_1,j_2,j_3}_{i_1,i_2,i_3}$ depend on Fermat-curve variables via cyclic weight functions, see (33). The conjugation by the $R$-matrix is a rational automorphism of the ultra-local Weyl algebra at the $N$-th root of unity. The representation of this automorphism as a functional mapping in the space of the parameters of the ultra-local Weyl algebra allows us to obtain the free parameterization of the MTE. By "free parameterization" we mean that we leave free which solution of the functional tetrahedron equation (72) with which boundary conditions will be chosen. We express the Fermat-curve variables (and so the Boltzmann weights) in terms of an independent set of eight continuous parameters and specify the sixteen phases which can be chosen independently. We derive a general expression for the scalar factor of the MTE. For the simplest non-trivial case $N = 2$ the MTE is written out explicitly. In this case it contains 256 linearly independent components.

The MTE allow to obtain a wide class of new integrable models: The $R$-matrices may be combined into the cubic blocks obeying globally the usual TE by due to the validity of the local MTE-s. The advantage of the free parameterization presented here
is that it allows to get the appropriate parameterization for blocks of any size. This is the subject of a forthcoming paper.

New integrable 2-dimensional lattice models with parameters living on higher Riemann surfaces can be obtained from the MTE by a contraction process which has been described in [13].

A further important application of the MTE concerns the following: As usual the TE leads to the commutativity of the layer-to-layer transfer matrices, while the MTE can be used to obtain exchange relations for the layer-to-layer transfer matrices. The exchange relations are related to isospectrality deformations and form the basis for a functional Bethe ansatz for three dimensional integrable spin models, see [18].

Note finally, that starting from the results of this paper, we can consider several limits of the parameterization, which are connected to various degenerations of the weights. The usual Tetrahedron equation of [4] follows from the MTE in the special regime when the free parameters $u_j, w_j, j = 1 \ldots 6$ belong to the submanifold of $\mathbb{C}^{12}$ defined by

$$u_i^N - R_{i,j,k}^{(f)} \cdot u_i^N = w_i^N - R_{i,j,k}^{(f)} \cdot w_i^N = 0.$$  \hspace{1cm} (97)

This variety may be parameterized in terms of spherical geometry data. E.g. $R_{1,2,3}$ may be associated with the spherical triangle with the dihedral angles $\theta_1, \theta_2, \theta_3$ and

$$\kappa_1^N = \tan^2 \frac{\theta_1}{2}, \quad \kappa_2^N = \cot^2 \frac{\theta_2}{2}, \quad \kappa_3^N = \tan^2 \frac{\theta_3}{2}.$$ \hspace{1cm} (98)

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