NEW PARTITION IDENTITIES FROM $C^{(1)}_{\ell}$-MODULES

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Abstract. In this paper we conjecture combinatorial Rogers-Ramanujan type colored partition identities related to standard representations of the affine Lie algebra of type $C^{(1)}_\ell$, $\ell \geq 2$, and we conjecture similar colored partition identities with no obvious connection to representation theory of affine Lie algebras.

1. Introduction

The seminal work [LW] of J. Lepowsky and R. Wilson on a Lie-theoretic interpretation of the Rogers-Ramanujan identities led to the discovery of numerous new combinatorial identities, like in [C] or [MP]. Recently several identities in the style of the Rogers-Ramanujan identities related to the representation theory of affine Lie algebras have appeared, let us mention only [KR] and [BJSM]. On the other side, some parts of representation theory lead to Rogers-Ramanujan type colored partition identities, let us mention only [DK] and [PS1] for this vein of research.

In this paper we conjecture combinatorial Rogers-Ramanujan type colored partition identities related to standard representations of the affine Lie algebra of type $C^{(1)}_\ell$, $\ell \geq 2$, and we conjecture similar colored partition identities with no obvious connection to representation theory of affine Lie algebras.

In Section 3 we start with the array of natural numbers $\mathcal{N}_5$ composed as a multiset of two copies of the set of natural numbers $\mathbb{N}$ and the additional set of odd numbers, arranged in 5 rows, with diagonals of width $w = 5$. Such an array appears naturally in the representation theory of the affine Kac-Moody Lie algebra $\hat{g}$ of type $C^{(1)}_2$ and it is expected that colored partitions on $\mathcal{N}_5$, satisfying certain difference and initial conditions, should parametrize bases of standard $\hat{g}$-modules—see Remark 3.4 below. In Conjecture 3.3 we guess, inspired by [T], a possible form of these colored partitions and, by a computing experiment, we conjecture the corresponding Rogers-Ramanujan type colored partition identities. Numerical evidence supports the conjecture for colored partitions on the array $\mathcal{N}_{2\ell+1}$, related to all standard modules for affine Lie algebra of type $C^{(1)}_\ell$, $\ell \geq 2$.

In Section 4 we start with the array of natural numbers $\mathcal{N}_4$ composed as a multiset of two copies of the set of natural numbers $\mathbb{N}$, arranged in 4 rows, with diagonals of width $w = 4$. In analogy with the “$w$ odd case”, in Conjecture 4.1 we conjecture similar colored partition identities for all $w = 2\ell$, $\ell \geq 2$, with no obvious connection to representation theory of affine Lie algebras, but again supported by numerical evidence.

The arrays of natural numbers

$$\mathcal{N}_2, \mathcal{N}_3, \mathcal{N}_4, \mathcal{N}_5, \mathcal{N}_6, \mathcal{N}_7, \ldots$$
form a natural sequence and for each \(\mathcal{N}_{2\ell}\) and \(\mathcal{N}_{2\ell+1}, \ell \geq 1\), and all nonnegative integers \(k_0, k_1, \ldots, k_\ell\), \(k = k_0 + k_1 + \cdots + k_\ell > 0\), we have a class of \((k_0, k_1, \ldots, k_\ell)\)-admissible colored partitions (defined in \(3.3\) and \(3.4\) below) for which we conjecture Rogers-Ramanujan type combinatorial identities. For \(w = 2\ell = 2\) and \(k = 1\) we have the two Rogers-Ramanujan identities, and for \(w = 2\ell + 1 = 3\) and \(k = 1\) we have two identities (in some sense) equivalent to the two Capparelli identities.\(^{1}\)

In Section 5 we describe an algorithm for constructing admissible colored partitions, and in the Appendix we give a Python code for counting admissible colored partitions.

### 2. Lepowsky’s Product Formula

In this section we give the Lie theoretic origin of the product expression in Conjecture 3.3 below. Note however that Conjecture 3.3 is a purely combinatorial statement.

By \(C_\ell^{(1)}\) we denote the affine Lie algebra of type \(C_\ell^{(1)}\), see e.g. [K], Table Aff 1, page 54 and (7.2.1), page 98. By \(L(k_0, \ldots, k_\ell)\) we denote the irreducible highest weight module \(L(\lambda)\) with highest weight \(\lambda = k_0\lambda_0 + \cdots + k_\ell\lambda_\ell\), see e.g. [K], page 147. The principally specialized character \(\text{ch}_q L_C^{(1)}(k_0, \ldots, k_\ell)\) is defined in [K], page 152 together with §10.9, page 181. Associated to \(L(k_0, \ldots, k_\ell)\) set \(k = k_0 + k_1 + \cdots + k_\ell\).

Let \(s_0, s_1, \ldots, s_\ell \in \mathbb{N}, s = s_0 + s_1 + \cdots + s_\ell\). We define the following triangular scheme of natural numbers:

\[
\begin{align*}
D(s_0, s_1, \ldots, s_\ell) &= \{s_0, \ldots, 2s - s_0\} \text{ has } 2\ell + 1 \text{ ascending numbers with increments } s_1, s_2, \ldots, s_\ell, s_\ell, \ldots, s_2, s_1; \\
D(s_1, \ldots, s_\ell) &= \{s_1, \ldots\} \text{ has } 2\ell - 1 \text{ ascending numbers with increments } s_2, \ldots, s_\ell, s_\ell, \ldots, s_2; \\
D(s_2, \ldots, s_\ell) &= \{s_2, \ldots\} \text{ has } 2\ell - 3 \text{ ascending numbers with increments } s_3, \ldots, s_\ell, s_\ell, \ldots, s_3; \\
&\vdots \\
D(s_\ell-1, s_\ell) &= \{s_{\ell-1}, s_{\ell-1} + s_\ell, s_{\ell-1} + 2s_\ell\}; \\
D(s_\ell) &= \{s_\ell\}.
\end{align*}
\]

**Example 2.1.** For example, for \((s_0, s_1, s_2, s_3, s_4) = (3, 2, 1, 1, 2)\) we have

\[
\begin{align*}
D(3, 2, 1, 1, 2) &= \{3, 5, 6, 7, 9, 11, 12, 13, 15\} \\
D(2, 1, 1, 2) &= \{2, 3, 4, 6, 8, 9, 10\} \\
D(1, 1, 2) &= \{1, 2, 4, 6, 7\} \\
D(1, 2) &= \{1, 3, 5\} \\
D(2) &= \{2\}
\end{align*}
\]

Note that we can obtain \(D(s_{\ell+1}, \ldots, s_\ell)\) from \(D(s_r, \ldots, s_\ell)\) by eliminating endpoints in \(D(s_r, \ldots, s_\ell)\) and then subtracting \(s_r\) from the remaining elements. We define the congruence triangle as the multiset

\[
\Delta(s_1, \ldots, s_\ell) = D(s_1, \ldots, s_\ell) \cup D(s_2, \ldots, s_\ell) \cup \cdots \cup D(s_\ell)
\]

and we denote by \(\{0\}^\ell\) the multiset consisting of \(\ell\) copies of 0.

\(^{1}\)See Remarks 4.3 and 4.4 below.
Now we can state Lepowsky’s product formula for $C^{(1)}_{\ell}$, $\ell \geq 2$ (cf. [L], [B]):

$$\text{ch}_q L_{C^{(1)}_{\ell}}(k_0, k_1, \ldots, k_\ell) = \prod_{a \in \{0\}^\ell \cup D(k_0+1,k_1+1,\ldots,k_\ell+1)} \prod_{b \in \Delta(k_1+1,\ldots,k_\ell+1)} \prod_{j \equiv a, \pm b \mod (2\ell+2k+2)} (1 - q^j)^{1 - (1 - q^j)^{-1}}.$$  

**Example 2.2.** By using Example 2.1 we see that the principally specialized character $\text{ch}_q L_{C^{(1)}_{\ell}}(2, 1, 0, 0, 1)$ is equal to

$$\prod_{j \text{ odd; } j \equiv 1, 1, 3, 3, 5, 5, 6, 6, 7, 7, 8, 8, 9, 9, 10, 10, 11, 11, 12, 13, 13, 14, 14, 15, 15, 16, 16, 17, 17 \mod 18} (1 - q^j)^{-1}.$$  

Note that in this product the factor $(1 - q^1)^{-1}$ appears three times.

3. Arrays with odd width $w \geq 5$

Let $N = N_5 = N_{C^{(1)}_2}$ be the array of natural numbers

$$\begin{array}{cccccc}
1 & 3 & 5 & 7 & 9 \\
2 & 4 & 6 & 8 & 10 \\
1 & 3 & 5 & 7 & 9 \\
2 & 4 & 6 & 8 & 10 \\
1 & 3 & 5 & 7 & 9 \\
\end{array}$$

(3.1)

This array consists of two copies of the set of natural numbers $\mathbb{N}$ and the additional set of odd numbers, arranged in 5 rows, with diagonals of width $w = 5$. Numbers increase by one going to the right on any diagonal. We shall consider elements in these sets as different, say “colored” by their position in the array. For example, the number 7 appears three times on three different places of the array $N$ and we consider 7 in the first row different from the other two. We say that two elements in an array are adjacent if they are simultaneously on two adjacent rows and two adjacent diagonals. For example, 6 and 8 in the second row are adjacent to 7 in the first row and, just as well, adjacent to 7 in the third row. We say that the set $\{a_1, a_2, a_3, \ldots\}$ is a downward path $Z$ in an array if $a_i$ is in the $i$-th row and if $(a_i, a_{i+1})$ is a pair of two adjacent elements for all $i$. For example, $Z = \{7, 6, 5, 4, 5\}$ is a downward path in $N$ and there are altogether $2^4$ downward paths through 7 in the first row. In Section 3 we shall consider downward paths which start from the top row, but need not reach the bottom row. $Z = \{7, 6, 5, 4\}$ is an example of such downward path—we shall say that this $Z = \{7, 6, 5, 4\}$ ends at 4 in the fourth row.

We consider colored partitions

$$n = \sum_{a \in N} f_a \cdot a,$$

where $f_a$ is the frequency of the part $a \in N$ in the colored partition (3.2) of $n$. Let $k_0, k_1, k_2 \in \mathbb{N}_0$, $k = k_0 + k_1 + k_2 > 0$. We say that an array of frequencies $F$

$$\begin{array}{cccccc}
f_1 & f_3 & f_5 & f_7 \\
f_2 & f_4 & f_6 & f_8 \\
f_1 & f_3 & f_5 & f_7 \\
f_2 & f_4 & f_6 & f_8 \\
f_1 & f_3 & f_5 & f_7 \\
\end{array}$$

(3.3)

is a set of frequencies for $n = \sum_{a \in N} f_a \cdot a$. Let $k_0, k_1, k_2 \in \mathbb{N}_0$, $k = k_0 + k_1 + k_2 > 0$. We say that an array of frequencies $F$
is \((k_0, k_1, k_2)\)-admissible if the extended array of frequencies \(F^{(k_0, k_1, k_2)}\)

\[
\begin{array}{cccccc}
  k_2 & f_1 & f_3 & f_5 & f_7 \\
  0 & f_2 & f_4 & f_6 & f_8 \\
  k_1 & f_1 & f_3 & f_5 & f_7 & \ldots \\
  0 & f_2 & f_4 & f_6 & f_8 \\
  k_0 & f_1 & f_3 & f_5 & f_7 \\
\end{array}
\]

(3.4)

satisfies the difference condition

\[
\sum_{m \in \mathbb{Z}} m \leq k
\]

for all downward paths \(Z\) in \(F^{(k_0, k_1, k_2)}\). So, for example, \(f_1\) in the first row must be \(\leq k_2\) because of (3.5) for the downward path \(Z = \{f_1, 0, k_1, 0, k_0\}\). We say that colored partitions (3.2) with \((k_0, k_1, k_2)\)-admissible arrays of frequencies (3.3) are \((k_0, k_1, k_2)\)-admissible colored partitions.

As explained, we consider the natural numbers at different places in the array (3.1) as different. Likewise, in the array of frequencies (3.3) the entry \(f_1\) in the first row denotes the frequency of the part 1 in the first row, which may be different from the entry \(f_1\) in the third row denoting the frequency of the part 1 in the third row. However, sometimes we need to write explicitly the coloring of elements in the array (3.1) and change the notation of frequency arrays (3.3) and extended frequency arrays (3.4) accordingly, like in the following example:

**Example 3.1.** Here we list all \((2, 0, 0)\)-admissible colored partitions for \(n \leq 8\). First we write explicitly one possible coloring of elements in the array (3.1)

\[
\begin{array}{cccccccc}
  1_1 & 3_1 & 5_1 & 7_1 & 9_1 \\
  2_1 & 4_1 & 6_1 & 8_1 & 10_1 \\
  1_2 & 3_2 & 5_2 & 7_2 & 9_2 \\
  2_2 & 4_2 & 6_2 & 8_2 & 10_2 \\
  1_3 & 3_3 & 5_3 & 7_3 & 9_3 \\
\end{array}
\]

(3.6)

and change the notation for the extended array of frequencies (3.4) accordingly

\[
\begin{array}{cccccccc}
  0 & f_{1_1} & f_{3_1} & f_{5_1} & f_{7_1} \\
  0 & f_{2_1} & f_{4_1} & f_{6_1} & f_{8_1} \\
  0 & f_{1_2} & f_{3_2} & f_{5_2} & f_{7_2} \\
  0 & f_{2_2} & f_{4_2} & f_{6_2} & f_{8_2} \\
  2 & f_{1_3} & f_{3_3} & f_{5_3} & f_{7_3} \\
\end{array}
\]

(3.7)
Then we have \((2, 0, 0)\)-admissible colored partitions for \(n \leq 8\):

\[
\begin{array}{c}
1 &= 1_3 \\
2 &= 2_2 = 1_3 + 1_3 \\
3 &= 3_2 = 3_3 + 2_2 + 1_3 \\
4 &= 4_1 = 4_2 = 3_2 + 1_3 = 3_3 + 1_3 = 2_2 + 2_2 \\
5 &= 5_1 = 5_2 = 5_3 = 4_1 + 1_3 = 4_2 + 1_3 = 3_2 + 2_2 = 3_3 + 2_2 = 3_3 + 1_3 + 1_3 \\
6 &= 6_1 = 6_2 = 5_1 + 1_3 = 5_2 + 1_3 = 5_3 + 1_3 = 4_1 + 2_2 = 4_2 + 2_2 = 4_2 + 2_2 = 4_2 + 1_3 + 1_3 \\
7 &= 7_1 = 7_2 = 7_3 = 6_1 + 1_3 = 6_2 + 1_3 = 5_1 + 2_2 = 5_2 + 2_2 = 5_3 + 2_2 = 5_3 + 1_3 + 1_3 \\
8 &= 8_1 = 8_2 = 7_1 + 1_3 = 7_2 + 1_3 = 7_3 + 1_3 = 6_1 + 2_2 = 6_2 + 2_2 = 6_1 + 1_3 + 1_3 \\
&\quad = 6_2 + 1_3 + 1_3 = 5_1 + 3_2 = 5_1 + 3_3 = 5_2 + 3_2 = 5_2 + 3_3 = 5_3 + 3_2 = 5_3 + 3_3 \\
&\quad = 5_2 + 13 + 13 = 5_3 + 13 + 13 = 4_1 + 3_2 = 4_1 + 3_3 = 4_2 + 3_2 = 4_2 + 3_3 \\
&\quad = 4_2 + 2_2 + 1_3 = 3_2 + 3_3 + 1_3 = 3_3 + 3_3 + 1_3 \\
\end{array}
\]

Note that for any \((2, 0, 0)\)-admissible colored partition \(n = \sum_{a \in \mathbb{N}} f_a \cdot a\) difference conditions (3.5) imply

\[f_{11} = f_{21} = f_{31} = f_{12} = 0.\]

Also note that, for example, \(8 = 3_3 + 3_3 + 1_3 + 1_3\) is a \((2, 0, 0)\)-admissible colored partition, and \(8 = 3_2 + 3_2 + 1_3 + 1_3\) is not since difference condition (3.5) is violated:

\[f_{32} + f_{13} = 2 + 2 = 4 > 2.\]

**Remark 3.2.** The partitions in the above example are (essentially) the partitions in Example 3 in \([\text{PS}2]\); only the coloring of the array (3.7) is different.

We extend these notions for \(C^{(1)}_\ell\), \(\ell \geq 1\), by starting with the array \(\mathcal{N} = \mathcal{N}_{2\ell+1} = \mathcal{N}_{C^{(1)}_\ell}\) of \(\ell\) copies of the set of natural numbers \(\mathbb{N}\) and the additional set of odd numbers, arranged in \(2\ell + 1\) rows and diagonals of width \(w = 2\ell + 1\); with numbers in \(\mathcal{N}\) increasing by one going to the right on any diagonal. For example, for \(\ell = 3\) we have the extended array of frequencies \(F^{(k_0, k_1, k_2, k_3)}\)

\[
\begin{array}{c|cccccccc}
    & k_3 & f_1 & f_2 & f_3 & f_4 & f_5 & f_6 & f_7 \\
\hline
k_2 & f_1 & f_2 & f_3 & f_4 & f_5 & f_6 & f_7 & \ldots \\
0 & 0 & f_2 & f_4 & f_6 & f_8 & & & \\
k_1 & f_1 & f_3 & f_5 & f_7 & & & & \\
0 & 0 & f_2 & f_4 & f_6 & f_8 & & & \\
k_0 & f_1 & f_3 & f_5 & f_7 & & & & \\
0 & 0 & f_2 & f_4 & f_6 & f_8 & & & \\
\end{array}
\]

and the corresponding notion of \((k_0, k_1, k_2, k_3)\)-admissible colored partitions on the array \(\mathcal{N}_7\).

**Conjecture 3.3.** Let \(\ell \geq 2\). The principally specialized character

\[
\prod_{a \in \{0\}^\ell \cup D(k_0+1,k_1+1,\ldots,k_\ell +1); b \in \Delta(k_0+1,\ldots,k_\ell+1); j \equiv a \pm b \mod (2\ell+2k+2)} (1-q^{-j})^\ell 
\]

\[
\prod_{j \text{ odd}} (1-q^j) \prod_{j \in \mathbb{N}} (1-q^j)^{\ell}
\]
is the generating function for the number of \((k_0, k_1, \ldots, k_\ell)\)-admissible partitions

\[ n = \sum_{\alpha \in \mathcal{N}_{\ell+1}} f_\alpha \cdot a. \]

**Remark 3.4.** Conjecture [3,3] is true for \((1,0,\ldots,0)\)-admissible colored partitions and any \(\ell \geq 2\) (see [PS1]). In [PS2] Conjecture [3,3] is formulated for \((k,0,\ldots,0)\)-admissible colored partitions with \(\ell \geq 2\) and \(k \geq 2\), and it was checked for some small values of \(\ell, k\) and \(n\) (cf. [P]).

In [MP] the product formula for the generating function for the number of \((k_0, k_1)\)-admissible partitions on the array \(\mathcal{N}_3\) is given; in the \(\ell = 1\) case it is Lepowsky’s product formula for \(A_1^{(1)}\) and the key ingredient—a construction of combinatorial bases of standard \(A_1^{(1)}\)-modules—is independently obtained in [FLM] and [P].

The combinatorial identities for \((1,0)\)-admissible partitions and for \((0,1)\)-admissible partitions are equivalent\(^2\) to the two Capparelli identities [C]. Moreover, it seems that these identities are related to the purely combinatorial approach in [AAG], based on Capparelli’s identity which was found using representation theory of \(A_2^{(2)}\).

**Example 3.5.** Conjecture [3,3] is based on a computer experiment. Here we present some results for admissible partitions for \(n\) up to 20.

We write

\[(1,0,1) \sim (r \equiv 1,1,3,4,6,7,9,9 \mod 10)\]

if the number of \((1,0,1)\)-admissible colored partitions of \(n\) is equal to the number of colored partitions of \(n\) with parts \(r \equiv 1,1,3,4,6,7,9,9 \mod 10\) for \(n \leq 20\) (here \(r \equiv 1,1 \mod 10\) means that parts \(r \equiv 1 \mod 10\) come in two colors). Since the parameters \((k_0, k_1, k_2)\) and \((k_2, k_1, k_0)\) give “isomorphic” colored partitions, we list below only mutually different conjectured identities.

For \(w = 5\) we have:

\[
\begin{align*}
(1,0,0) & \sim (r \text{ odd}; r \equiv 4 \mod 8), \\
(2,0,0) & \sim (r \text{ odd}; r \equiv 2,4,5,6,8 \mod 10), \\
(1,1,0) & \sim (r \text{ odd}; r \equiv 1,3,5,7,9 \mod 10), \\
(1,0,1) & \sim (r \equiv 1,1,3,4,6,7,9,9 \mod 10), \\
(0,2,0) & \sim (r \equiv 1,2,2,3,3,7,7,8,8,9 \mod 10), \\
(3,0,0) & \sim (r \text{ odd}; r \equiv 2,3,4,5,6,7,8,9,10 \mod 12), \\
(2,1,0) & \sim (r \text{ odd}; r \equiv 1,2,4,5,6,7,8,10,11 \mod 12), \\
(2,0,1) & \sim (r \text{ odd}; r \equiv 1,2,4,5,6,7,8,10,11 \mod 12), \\
(1,2,0) & \sim (r \text{ odd}; r \equiv 1,2,3,4,6,8,9,10,11 \mod 12), \\
(0,3,0) & \sim (r \text{ odd}; r \equiv 2,3,4,5,6,7,8,9,10 \mod 12), \\
\end{align*}
\]

\(^2\)In [MP] certain spanning sets \(B(\Lambda_0) \subset L(\Lambda_0)\) and \(B(\Lambda_1) \subset L(\Lambda_1)\) of the two fundamental \(A_1^{(1)}\)-modules are constructed. The following three statements are equivalent: (i) \(B(\Lambda_0)\) and \(B(\Lambda_1)\) are linearly independent, (ii) the generating functions for \((1,0)\)-admissible and \((0,1)\)-admissible partitions are the principally specialized characters \(ch_qL(\Lambda_0)\) and \(ch_qL(\Lambda_1)\), and (iii) the two Capparelli identities hold.
For $w = 7$ we have:

\[(3, 0, 1) \sim (r \text{ odd}; \; r \equiv 1, 3, 4, 5, 7, 8, 9, 11 \mod 12),\]
\[(0, 1, 1, 0) \sim (r \text{ odd}; \; r \equiv 1, 2, 3, 5, 7, 9, 10, 11 \mod 12),\]
\[(2, 0, 0, 1) \sim (r \text{ odd}; \; r \equiv 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13 \mod 14),\]
\[(2, 0, 0, 2) \sim (r, r \text{ odd}; \; r \equiv 2, 2, 4, 6, 6, 10, 10, 12, 14, 14 \mod 16).\]

For $w = 9$ we have:

\[(1, 0, 0, 0, 1) \sim (r \equiv 1, 1, 3, 3, 4, 4, 5, 6, 6, 8, 9, 10, 10, 11, 11, 13, 13 \mod 14),\]
\[(0, 1, 1, 0, 0) \sim (r \text{ odd}; \; r \equiv 1, 2, 3, 4, 5, 7, 9, 10, 11, 12, 13 \mod 14),\]
\[(0, 1, 1, 0, 1) \sim (r \text{ odd}; \; r \equiv 1, 1, 2, 3, 4, 4, 6, 6, 7, 8, 9, 10, 10, 12, 12, 13, 14, 15 \mod 16),\]
\[(2, 1, 0, 0, 1) \sim (r, r \text{ odd}; \; r \equiv 1, 2, 4, 4, 5, 6, 7, 8, 9, 10, 10, 11, 12, 13, 14, 14, 16, 17 \mod 18).\]

**Example 3.6.** In the following identities, the right hand sides can be interpreted as the number of colored partitions satisfying congruence conditions, with the extra requirement that in one color the parts have to be distinct.

Associated to the module $L(0, 1, 0)$ we have that, for $n \leq 20$, the number of $(0, 1, 0)$-admissible colored partitions of $n$ equals

\[
\text{coeff}_{q^n} \prod_{r \equiv 2 \mod 4} (1 + q^r) / \prod_{r \equiv 1, 3, 5, 7 \mod 8} (1 - q^r).
\]

Associated to the module $L(1, 1, 1)$ we have that, for $n \leq 20$, the number of $(1, 1, 1)$-admissible colored partitions of $n$ equals

\[
\text{coeff}_{q^n} \prod_{r \text{ odd}} (1 + q^r) / \prod_{r \text{ odd}} (1 - q^r)^2.
\]

4. Arrays with even width $w \geq 4$

Let $N^e = N_4$ be the array of natural numbers

\[
\begin{array}{cccccc}
1 & 3 & 5 & 7 & 9 \\
2 & 4 & 6 & 8 & 10 & \cdots \\
1 & 3 & 5 & 7 & 9 \\
2 & 4 & 6 & 8 & 10 \\
\end{array}
\]

This array consists of two copies of the set of natural numbers $\mathbb{N}$ arranged in 4 rows, with diagonals of width $w = 4$. We consider colored partitions

\[
(4.2) \quad n = \sum_{a \in N^e} f_a \cdot a,
\]
where \( f_a \) is the frequency of the part \( a \in \mathcal{N}^c \) in the colored partition \( \{1,2\} \) of \( n \).

Let \( k_0, k_1, k_2 \in \mathbb{N}_0, k = k_0 + k_1 + k_2 > 0 \). We say that an array of frequencies \( \mathcal{F}^c \)
\[
\begin{array}{ccccccc}
    f_1 & f_2 & f_3 & f_4 & f_5 & f_6 & f_7 \\
    f_1 & f_2 & f_3 & f_4 & f_5 & f_6 & f_7 \\
    f_2 & f_3 & f_4 & f_5 & f_6 & f_7 & \ldots \\
\end{array}
\]
(4.3)
is \( (k_0, k_1, k_2)^c \)-admissible if the extended array of frequencies \( \mathcal{F}^{c(k_0,k_1,k_2)} \)
\[
\begin{array}{ccccccc}
    k_2 & 0 & f_2 & f_3 & f_4 & f_5 & f_7 \\
    k_1 & f_1 & f_2 & f_3 & f_4 & f_5 & f_7 \\
    k_0 & f_1 & f_2 & f_3 & f_4 & f_5 & f_7 \\
\end{array}
\]
(4.4)
satisfies the difference condition
\[
\sum_{m \in \mathcal{Z}} m \leq k
\]
(4.5)
for all downward paths \( \mathcal{Z} \) in \( \mathcal{F}^{c(k_0,k_1,k_2)} \). So, for example, \( f_1 \) in the first row must be \( \leq k_2 \) because of (4.5) for downward path \( \mathcal{Z} = \{f_1, 0, k_1, k_0\} \). We say that colored partitions (4.2) with \((k_0, k_1, k_2)^c\)-admissible arrays of frequencies (4.3) are \((k_0, k_1, k_2)^c\)-admissible colored partitions.

We extend these notions for \( \ell \geq 1 \) by starting with the array \( \mathcal{N}^c = \mathcal{N}_{2\ell} \) of \( \ell \) copies of the set of natural numbers \( \mathbb{N} \) arranged in \( 2\ell \) rows and diagonals of width \( w = 2\ell \); with numbers in \( \mathcal{N}^c \) increasing by one going to the right on any diagonal.

For example, for \( \ell = 3 \) \((w = 6)\) instead of (4.4) we have the extended array of frequencies \( \mathcal{F}^{c(k_0,k_1,k_2,k_3)} \)
\[
\begin{array}{ccccccc}
    k_3 & 0 & f_1 & f_2 & f_3 & f_4 & f_5 \\
    k_2 & 0 & f_1 & f_2 & f_3 & f_4 & f_5 \\
    k_1 & f_1 & f_2 & f_3 & f_4 & f_5 & f_7 \\
    k_0 & f_1 & f_2 & f_3 & f_4 & f_5 & f_7 \\
\end{array}
\]
(4.6)
and the corresponding notion of \((k_0, k_1, k_2, k_3)^c\)-admissible colored partitions on the array \( \mathcal{N}_6 \).

**Conjecture 4.1.** Let \( k_0, k_1, \ldots, k_\ell \in \mathbb{N}_0, k = k_0 + k_1 + \cdots + k_\ell > 0 \). Then the generating function for the number of \((k_0, k_1, \ldots, k_\ell)^c\)-admissible colored partitions
\[
n = \sum_{a \in \mathcal{N}_{2\ell}} f_a \cdot a
\]
is the infinite periodic product
\[
\prod_{a \in \{0\}^c: b \in \Delta(k_1+1, \ldots, k_\ell+1), j \equiv a, b \mod (2\ell+2k+1)(1-q^j)} (1-q^j).
\]
(4.7)

**Example 4.2.** By using Example 2.1 for the congruence triangle \( \Delta(2,1,1,2) \), we see that the conjectured product (4.7) for \((2,1,0,0,1)^c\)-admissible colored partitions is
\[
\prod_{j \equiv 1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17 \mod 17} (1-q^j)^{-1}.
\]
Remark 4.3. Conjecture 4.1 is true for $\ell = 1$: the extended array of frequencies $F^e(k_0, k_1)$ is true for
\begin{equation}
\begin{array}{ccccccc}
k_1 & f_1 & f_3 & f_5 & f_7 & \cdots \\
k_0 & f_2 & f_4 & f_6 & f_8 & & \\
\end{array}
\end{equation}
and $(k_0, k_1)^e$-admissible colored partitions are classical partitions
\[ n = \sum_{a \in \mathbb{N}} f_a \cdot a \]
satisfying difference and initial conditions
\[ f_a + f_{a+1} \leq k, \quad f_1 \leq k_1. \]
So the generating functions for the number of $(1, 0)^e$-admissible and $(0, 1)^e$-admissible partitions are the product sides of two Rogers-Ramanujan identities, and for $k = k_0 + k_1 > 1$ we have the product sides of Gordon identities (cf. [A1], [A2], [G]). These combinatorial identities have a Lie-theoretic interpretation (see [LW]), but for $2\ell > 2$ there is no obvious connection of $(k_0, k_1, \ldots, k_\ell)^e$-admissible colored partitions with representation theory of affine Lie algebras.

Example 4.4. In this example we write
\[(0, 0, 1)^e \sim (r \equiv 1, 3, 4, 6 \mod 7)\]
if the number of $(0, 0, 1)^e$-admissible colored partitions of $n$ is equal to the number of colored partitions of $n$ with parts $r \equiv 1, 3, 4, 6 \mod 7$ for $n \leq 20$.

For $w = 2$ we have Rogers-Ramanujan and Gordon identities:
\[(1, 0)^e \sim (r \equiv 2, 3 \mod 5), \quad (0, 1)^e \sim (r \equiv 1, 4 \mod 5), \quad (2, 0)^e \sim (r \equiv 2, 3, 4, 5 \mod 7), \quad (1, 1)^e \sim (r \equiv 1, 3, 4, 6 \mod 7), \quad (0, 2)^e \sim (r \equiv 1, 2, 5, 6 \mod 7), \quad (3, 0)^e \sim (r \equiv 2, 3, 4, 5, 6, 7 \mod 9), \quad (2, 1)^e \sim (r \equiv 1, 3, 4, 5, 6, 8 \mod 9), \quad (1, 2)^e \sim (r \equiv 1, 2, 4, 5, 7, 8 \mod 9), \quad (0, 3)^e \sim (r \equiv 1, 2, 3, 6, 7, 8 \mod 9).\]

For $w = 4$ we have:
\[(1, 0, 0)^e \sim (r \equiv 2, 3, 4, 5 \mod 7), \quad (0, 1, 0)^e \sim (r \equiv 1, 2, 5, 6 \mod 7), \quad (0, 0, 1)^e \sim (r \equiv 1, 3, 4, 6 \mod 7), \quad (2, 0, 0)^e \sim (r \equiv 2, 3, 4, 5, 6, 7 \mod 9), \quad (1, 1, 0)^e \sim (r \equiv 1, 2, 3, 4, 5, 6, 7, 8 \mod 9), \quad (1, 0, 1)^e \sim (r \equiv 1, 2, 3, 4, 5, 6, 7, 8 \mod 9), \quad (0, 2, 0)^e \sim (r \equiv 1, 2, 3, 6, 7, 8 \mod 9), \quad (0, 1, 1)^e \sim (r \equiv 1, 1, 3, 4, 5, 6, 8, 8 \mod 9), \quad (0, 0, 2)^e \sim (r \equiv 1, 2, 3, 4, 5, 6, 7, 8 \mod 9),\]
(3, 0, 0)^c \sim (r \equiv 2, 3, 4, 5, 6, 7, 8, 9 \mod 11),
(2, 1, 0)^c \sim (r \equiv 2, 3, 4, 5, 6, 7, 8, 9, 10 \mod 11),
(2, 0, 1)^c \sim (r \equiv 2, 3, 4, 5, 6, 7, 8, 9, 10 \mod 11),
(1, 2, 0)^c \sim (r \equiv 2, 3, 4, 5, 6, 7, 8, 9, 10 \mod 11),
(1, 1, 1)^c \sim (r \equiv 1, 1, 2, 3, 4, 5, 6, 7, 8, 10, 10 \mod 11),
(1, 0, 2)^c \sim (r \equiv 1, 2, 3, 4, 5, 6, 8, 9, 9, 10 \mod 11),
(0, 3, 0)^c \sim (r \equiv 2, 3, 3, 4, 5, 7, 8, 9, 10 \mod 11),
(0, 2, 1)^c \sim (r \equiv 2, 1, 2, 3, 4, 5, 6, 7, 9, 10, 10 \mod 11),
(0, 1, 2)^c \sim (r \equiv 1, 2, 4, 5, 6, 7, 9, 10, 10 \mod 11),
(0, 0, 3)^c \sim (r \equiv 1, 2, 3, 3, 4, 5, 6, 8, 9, 10 \mod 11).

For \( w = 6 \) we have:
(1, 0, 0, 0)^c \sim (r \equiv 2, 3, 4, 5, 6, 7 \mod 9),
(0, 1, 0, 0)^c \sim (r \equiv 1, 2, 4, 5, 7, 8 \mod 9),
(0, 0, 1, 0)^c \sim (r \equiv 1, 2, 3, 6, 7, 8 \mod 9),
(0, 0, 0, 1)^c \sim (r \equiv 1, 3, 4, 5, 6, 8 \mod 9),
(2, 0, 0, 0)^c \sim (r \equiv 2, 3, 4, 5, 6, 7, 8, 9 \mod 11),
(1, 1, 0, 0)^c \sim (r \equiv 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 \mod 11).

For \( w = 8 \) we have:
(0, 1, 1, 0, 1)^c \sim (r \equiv 1, 1, 1, 2, 3, 4, 4, 4, 6, 6, 7, 9, 9, 11, 11, 12, 13, 14, 14, 14 \mod 15),
(2, 1, 0, 0, 1)^c \sim (r \equiv 1, 1, 2, 3, 4, 4, 5, 5, 5, 6, 6, 7, 7, 8, 8, 9, 10, 10, 11, 11, 12, 12, 12, 13, 13, 14, 14, 15, 15, 16, 16 \mod 17),
(0, 1, 1, 1, 1)^c \sim (r \equiv 1, 1, 1, 1, 3, 3, 3, 4, 5, 5, 5, 6, 7, 7, 8, 8, 9, 10, 10, 11, 11, 12, 12, 12, 13, 14, 14, 14, 16, 16, 16, 16 \mod 17).

Remark 4.5. It seems that for pairs (level \( k \), rank \( \ell \)) there is some sort of duality
\((k, \ell) \leftrightarrow (\ell, k)\).

In particular, the Rogers-Ramanujan case \( k = 1, \ w = 2 \) is self-dual and \( k = 2, \ w = 2 \) is dual to \( k = 1, \ w = 4 \). In the self-dual case \( k = 2, \ w = 4 \) we see that \((1, 1, 0)^c\)-admissible, \((1, 0, 1)^c\)-admissible and \((0, 0, 2)^c\)-admissible partitions have the same product formula, but already for \( n = 1 \) and \( n = 2 \) we see that three types of colored partitions on \( N_4 \) are mutually different.

5. An algorithm for constructing admissible arrays of frequencies

In this section we describe an algorithm for constructing \((k_0, k_1, \ldots, k_\ell)\)-admissible and \((k_0, k_1, \ldots, k_\ell)^c\)-admissible arrays of frequencies. First we consider the simplest case of \((k, 0, 0)\)-admissible arrays of frequencies \( \mathcal{F} \). The difference condition \((3.6)\) forces the extended array of frequencies \( \mathcal{F}^{(k,0,0)} \) to look like
\[
\begin{array}{cccccccc}
0 & 0 & 0 & f_5 & f_1 & f_7 \\
0 & 0 & f_4 & f_6 & f_8 \\
k & f_2 & f_3 & f_5 & f_3 & f_7 & \ldots \\
\end{array}
\]
In order to avoid any confusion and facilitate the exposition, here we have colored our arrays as in Example 3.1.

At the beginning we let $F = 0$, i.e. all the frequencies in $F$ are zero. Then we construct a nontrivial $(k, 0, 0)$-admissible array of frequencies by changing $F$ in steps. We start our construction from the top $5_1$ till the bottom $1_3$ of the first diagonal $\{5_1, 4_1, 3_2, 2_2, 1_3\} \subset \mathcal{N}$ of length 5, then from the top till the bottom of the second diagonal $\{7_1, 6_1, 5_2, 4_2, 3_3\}$ of length 5, and so on. At each step for $a \in \mathcal{N}$ we choose a frequency $f_a$ and determine the corresponding maximum

$$m_a = \max\{ \sum_{c \in Z} f_c | Z \text{ is a downward path which ends in } a \}.$$  

So we start with $a = 5_1$ and we choose any value $f_{5_1} \in \{0, 1, \ldots, k\}$. For the first point $5_1$ there is only one downward path $Z = \{5_1\}$ which ends in $5_1$, so

$$m_{5_1} = f_{5_1}.$$  

For the second point $4_1$ we should choose $f_{4_1}$. There are two downward paths which end in $4_1$: $Z_1 = \{5_1, 4_1\}$ and $Z_2 = \{3_1, 4_1\}$. Since $f_{3_1} = 0$, we have

$$m_{4_1} = f_{5_1} + f_{4_1},$$

and the level $k$ difference condition $m_{4_1} \leq k$ forces us to choose

$$f_{4_1} \leq k - f_{5_1}.$$  

At each step we choose $f_a$ and determine $m_a$, so assume we completed a list of frequencies $f_a$ and maxima $m_a$ in the first two diagonals and in the top two places $9_1, 8_1$ in the third diagonal. Next we should choose $f_b$ for $b = 7_2$. Denote the points $6_1$ and $8_1$—the points above and adjacent to $b$—as $x$ and $y$:

$$m_b = f_b + \max\{m_x, m_y\} \leq k.$$  

Then choose a frequency $f_b$ so that $f_b + \max\{m_x, m_y\} \leq k$. Since every downward path $Z$ comes to $b$ via $x$ or via $y$, it is clear that

$$m_b = f_b + \max\{m_x, m_y\} \leq k.$$  

In this sequence of steps we have constructed the frequencies $f_c$ for $c$ denoted as $x, y, b$ or $\bullet$ in (5.3), and all the other frequencies in $F$ are (still) 0. By construction, i.e. by the recursive condition (5.4) for each constructed $f_c$, the difference condition (3.5) holds for all downward paths $Z$ in $\mathcal{F}(k, 0, 0)$. Hence the (so far) constructed sequence of frequencies is $(k, 0, 0)$-admissible. In this way we proceed till the end of a finite (chosen in advance) number of diagonals.

**Remark 5.1.** Assume we want to construct and count all colored partitions

$$n = \sum_{a \in \mathcal{N}_k} f_a \cdot a \text{ for } n \leq 15,$$

with $(k, 0, 0)$-admissible frequencies $f_a$. Since the biggest part in a partition of $n \leq 15$ is at most 15, it is enough to consider only the first eight nontrivial diagonals of frequency array (5.7). We can write compactly the first eight full-length
diagonals in the array (3.1), the constructed part of the frequency array (5.3), and the constructed part of the maxima array as

\[(5.5)\]

\[
\begin{array}{cccccccccccc}
1_3 & 2_3 & 3_4 & 4_1 & 5_1 & f_{13} & f_{22} & f_{32} & f_{41} & f_{51} & m_{13} & m_{22} & m_{32} & m_{41} & m_{51} \\
3_3 & 4_2 & 5_2 & 6_1 & 7_1 & f_{33} & f_{42} & f_{52} & f_{61} & f_{71} & m_{33} & m_{42} & m_{52} & m_{61} & m_{71} \\
5_3 & 6_2 & 7_2 & 8_1 & 9_1 & \cdot & \cdot & f_{81} & f_{91} & \cdot & \cdot & m_{81} & m_{91} \\
7_3 & 8_2 & 9_2 & 10_1 & 11_1 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
9_3 & 10_2 & 11_2 & 12_1 & 13_1 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
11_3 & 12_2 & 13_2 & 14_1 & 15_1 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
13_3 & 14_2 & 15_2 & 16_1 & 17_1 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
15_3 & 16_2 & 17_2 & 18_1 & 19_1 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
\end{array}
\]

Then we can choose a frequency \(0 \leq f_{72} \leq k\) for \(7_2\) so that the recursive condition (5.4) holds, i.e.

\[(5.6)\]

\[m_{72} = f_{72} + \max\{m_{61}, m_{81}\} \leq k.\]

In this way we proceed till the end of the eighth row.

Now we consider, again for \(\ell = 2\), a construction of \((k_0, k_1, k_2)\)-admissible or \((k_0, k_1, k_2)\)\(^e\)-admissible arrays of frequencies \(F\) or \(F^e\) with non-zero frequencies in a finite (chosen in advance) number of diagonals. We denote with \(\circ\) the places of the array of not yet constructed frequencies in the chosen finite number of diagonals as

\[
\begin{array}{cccccccccc}
\circ & \circ & \circ & \circ & \circ & \circ & \circ & \circ & \circ \\
\circ & \circ & \circ & \circ & \circ & \circ & \circ & \circ & \circ \\
\circ & \circ & \circ & \circ & \circ & \circ & \circ & \circ & \circ \\
\circ & \circ & \circ & \circ & \circ & \circ & \circ & \circ & \circ \\
\end{array}
\]

and we extend them on the left with the prescribed fixed frequencies

\[
\begin{array}{cccccccccc}
k_2 & \circ & \circ & \circ & \circ & \circ & \circ & \circ & \circ \\
k_1 & k_1 & \circ & \circ & \circ & \circ & \circ & \circ & \circ \\
0 & 0 & \circ & \circ & \circ & \circ & \circ & \circ & \circ \\
0 & 0 & 0 & \circ & \circ & \circ & \circ & \circ & \circ \\
k_0 & k_0 & k_0 & \circ & \circ & \circ & \circ & \circ & \circ \\
k_0 & k_0 & k_0 & k_0 & \circ & \circ & \circ & \circ & \circ \\
\end{array}
\]

Note that added fixed frequencies satisfy the difference conditions (3.5) or (4.5).

Now the first diagonal is fixed and “constructed”, and the corresponding diagonal of the maxima is

\[
\begin{array}{cccccccccc}
k_2' & \circ & \circ & \circ & \circ & \circ & \circ & \circ & \circ \\
k_2' & \circ & \circ & \circ & \circ & \circ & \circ & \circ & \circ \\
k_2 & \circ & \circ & \circ & \circ & \circ & \circ & \circ & \circ \\
k_2 & \circ & \circ & \circ & \circ & \circ & \circ & \circ & \circ \\
k' & \circ & \circ & \circ & \circ & \circ & \circ & \circ & \circ \\
k' & \circ & \circ & \circ & \circ & \circ & \circ & \circ & \circ \\
k & \circ & \circ & \circ & \circ & \circ & \circ & \circ & \circ \\
\end{array}
\]

with \(k' = k_1 + k_2\) and \(k = k_0 + k_1 + k_2\). So we pass to the first point in the second diagonal, choose a frequency from the set \(\{0, 1, \ldots, k\}\) and determine the corresponding maximum. After that we pass to the second point and so on, just like before, except that in the second diagonal four or three frequencies are already

---

\(^\text{3}\)The diagram (5.5) is obtained from (5.1) by a (clockwise) 45 degree rotation, followed by the shear linear transformation \((x, y) \mapsto (x + y, y)\). In particular, the rows in (5.5) are obtained from diagonals in (5.1).
fixed and if the condition (3.5) or (4.5) does not hold, we should return to the
beginning of the diagonal and give another try with the frequency of the first point.
In the third diagonal we have to construct frequency for three points—the other
two or one are already given and fixed, and so on. It is clear that the constructed
sequence of frequencies is \((k_0, k_1, k_2)\)-admissible.

In the Python code below we consider the

\[
\begin{pmatrix}
  k_w & \circ & \circ \\
  k_{w-1} & k_w-1 & \circ \\
  k_{w-2} & k_{w-2} & \circ & \circ \\
  k_{w-3} & k_{w-3} & \circ & \circ & \circ \\
  \vdots & \vdots & \vdots & \vdots & \vdots \\
\end{pmatrix}
\]

and the corresponding notion of \([k_1, k_2, \ldots, k_{w-1}, k_w]\)-admissible colored partitions
on the array \(N_w\). Note that

- \((k_0, k_1, \ldots, k_\ell)\)-admissible = \([k_0, 0, k_1, 0, \ldots, 0, k_\ell]\)-admissible for \(w = 2\ell+1\),
- \((k_0, k_1, \ldots, k_\ell)^c\)-admissible = \([k_0, k_1, 0, \ldots, 0, k_\ell]\)-admissible for \(w = 2\ell\).

We conjecture product formulas for generating functions for the number of the cor-
responding admissible colored partitions, and it seems that for any other \([k_1, \ldots, k_w]\]
there is no infinite periodic product formula for the generating function for the num-
ber of the corresponding \([k_1, \ldots, k_w]\)-admissible colored partitions.

**Remark 5.2.** In higher ranks it may be convenient to write the extended \([k_1, \ldots, k_w]\)-admissible frequency arrays compactly as infinite matrices

\[
\begin{array}{cccccccc}
  f_{11} & f_{12} & f_{13} & f_{14} & f_{15} & f_{16} & f_{17} & f_{18} \\
  f_{21} & f_{22} & f_{23} & f_{24} & f_{25} & f_{26} & f_{27} & f_{28} \\
  f_{31} & f_{32} & f_{33} & f_{34} & f_{35} & f_{36} & f_{37} & f_{38} \\
  f_{41} & f_{42} & f_{43} & f_{44} & f_{45} & f_{46} & f_{47} & f_{48} \\
  f_{51} & f_{52} & f_{53} & f_{54} & f_{55} & f_{56} & f_{57} & f_{58} \\
  f_{61} & f_{62} & f_{63} & f_{64} & f_{65} & f_{66} & f_{67} & f_{68} \\
  f_{71} & f_{72} & f_{73} & f_{74} & f_{75} & f_{76} & f_{77} & f_{78} \\
  f_{81} & f_{82} & f_{83} & f_{84} & f_{85} & f_{86} & f_{87} & f_{88} \\
\end{array}
\]

with fixed prescribed frequencies in the upper left corner of the matrix, depending
on odd \(w = 2\ell+1\) or even \(w = 2\ell\). Here \(j = w\) denotes the left column, and \(j = 1\)
the right column. For \(\ell = 4\) we have matrices of the form

\[
\begin{pmatrix}
  k_1 & k_2 & k_3 & k_4 & k_5 & k_6 & k_7 & k_8 \\
  k_1 & k_2 & k_3 & k_4 & k_5 & k_6 & k_7 & * \\
  k_1 & k_2 & k_3 & k_4 & k_5 & k_6 & * & * \\
  k_1 & k_2 & k_3 & * & * & * & * & * \\
\end{pmatrix}
\quad \text{or} \quad
\begin{pmatrix}
  k_1 & k_2 & k_3 & k_4 & k_5 & k_6 & k_7 & k_8 \\
  k_1 & k_2 & k_3 & k_4 & k_5 & k_6 & * & * \\
  k_1 & k_2 & k_3 & * & * & * & * & * \\
  k_1 & k_2 & * & * & * & * & * & * \\
\end{pmatrix}
\]

For a frequency matrix (5.7) we assume that there are finitely many non-zero ele-
ments \(f_{ij}\) and we say that \(F\) has a finite support. We can write the matrix \(F\) as
an infinite sequence of rows

\[
F = (f_{ij})_{i=0,1,\ldots; j=w,\ldots,1}, \quad \phi_i = (f_{ij})_{j=w,\ldots,1}.
\]

Like in (5.7), for a frequency matrix \(F\) we have the associated maxima matrix

\[
M = (m_{ij})_{i=0,1,\ldots; j=w,\ldots,1},
\]
defined for \( i = 0 \) as
\[
m_{0j} = k_w + \cdots + k_{w-j+1}, \quad j = 1, \ldots, w,
\]
and for \( i = 1, 2, \ldots \) recursively like in (5.7).
\[
(5.10) \quad m_{i1} = f_{i1}, \quad m_{ij} = f_{ij} + \max\{m_{i-1,j-1}, m_{i,j-1}\}, \quad j = 2, \ldots, w.
\]
Our argument above shows that a frequency matrix \( F \) is \([k_1, \ldots, k_w]-\text{admissible if and only if}
\[
(5.11) \quad m_{ij} \leq k \quad \text{for all} \quad i = 1, 2, \ldots, \quad j = 1, \ldots, w.
\]
We can also write our arrays of natural numbers \( N_2, N_3, N_4, N_5, \ldots \) as infinite matrices \( N^0 = (n_{ij})_{i=0,1,\ldots}; j=w,\ldots,1, \quad n_{ij} = \max\{0,2i-j\}, \)
i.e. as infinite matrices \( N^0_2, N^0_3, N^0_4, N^0_5, \ldots \)
\[
\begin{array}{ccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 1 & 0 & 0 \\
2 & 3 & 1 & 2 & 3 & 0 & 1 \\
4 & 5 & 3 & 4 & 5 & 2 & 3 \\
6 & 7 & 5 & 6 & 7 & 4 & 5 \\
8 & 9 & 7 & 8 & 9 & 6 & 7 \\
10 & 11 & 9 & 10 & 11 & 8 & 9 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
\end{array}
\]
Then for each \([k_1, \ldots, k_w]-\text{admissible frequency matrix} \) we have a \([k_1, \ldots, k_w]-\text{admissible colored partition}
\[
N = \sum_{i=0}^{\infty} \sum_{j=1}^{w} f_{ij} n_{ij}.
\]

Example 5.3. Here we describe a construction of all \((0,1,0)-\text{admissible frequencies with the support in the first 5 diagonals}\) in the array \( N_5 \). By using the notation in \( \text{Remark } 5.2 \) we want to construct all \([0,0,1,0,0]-\text{admissible frequency matrices} \) \( F \), together with the associated maxima matrices \( M \),
\[
(5.12) \quad F = (\phi_0, \phi_1, \phi_2, \phi_3, \phi_4, \phi_5), \quad M = (\mu_0, \mu_1, \mu_2, \mu_3, \mu_4, \mu_5),
\]
with \( \phi_0 = (0,0,1,0,0), \phi_1 = (0,0,1,0,0), \phi_2 = (0,0,1,0,0), \phi_3 = (0,0,1,0,0), \)
\( \phi_4 = (0,0,1,0,0), \phi_5 = (0,0,1,0,0), \ldots \), and \( \mu_i \) is \( i \)-th row in \( M \). Denote by \( A(i) \) the set of all possible quintuples of frequencies in the \( i \)-th row, i.e. the set of quintuples of frequencies with the total sum \( \leq k = 1 \). \( A(0) \) is completely determined, and for the other we obviously have:
\[
A(0) = \{(0,0,1,0,0)\},
A(1) = \{(0,0,1,0,0)\},
A(2) = \{(0,0,0,0,0), (0,0,1,0,0), (0,0,0,1,0), (0,0,0,0,1)\},
A(3) = \{(0,0,0,0,0), (1,0,0,0,0), (0,1,0,0,0), (0,0,1,0,0), (0,0,0,1,0), (0,0,0,0,1)\},
A(4) = \{(0,0,0,0,0), (1,0,0,0,0), (0,1,0,0,0), (0,0,1,0,0), (0,0,0,1,0), (0,0,0,0,1)\},
A(5) = \{(0,0,0,0,0), (1,0,0,0,0), (0,1,0,0,0), (0,0,1,0,0), (0,0,0,1,0), (0,0,0,0,1)\}.
\]
If we use printouts from the Python code 21AAJC.py in the Appendix, for \( N = 6 \) and ‘highest weight’ = \([0, 0, 1, 0, 0]\), and if we activate ‘print( ’i =’, i, ’all fs =’,

all fs)” on line 76, we get $A(1), \ldots, A(5)$ as above (with mixed-up left and right). We obtain the first six rows of $N^0_5$ if we activate “print( 'i =', i, 'row1 =', row1)” on line 73.

We may construct $F$ in steps $i = 0, \ldots, 4$, and by using (5.10) at each step we determine the rows of the associated maxima matrix

\[ \phi_0, \phi_1, \ldots, \phi_i; \mu_0, \mu_1, \ldots, \mu_i \rightsquigarrow \phi_0, \phi_1, \ldots, \phi_i, \phi_i+1; \mu_0, \mu_1, \ldots, \mu_i, \mu_i+1, \phi_r \in A(r). \]

Since we are using (5.10) to determine $\mu_{i+1}$, we have a map

\[ (\phi_{i+1}, \mu_i) \mapsto \mu_{i+1}, \]

and if $\mu_{i+1}$ does not satisfy the criteria (5.11), we discard the newly constructed matrix from the further procedure. In Python code 21AAIC.py this function is defined on line 29 as “filter frequencies(fs, ms1, *ks)”.

Since in our construction we need only the last maxima row $\mu_i$ to determine whether the newly constructed frequency matrix in (5.13) is $[0, 0, 1, 0, 0]$-admissible, we could have discarded already used up $\mu_0, \mu_1, \ldots, \mu_{i-1}$. On the other hand, if we are interested in the corresponding $[0, 0, 1, 0, 0]$-admissible partitions, we can keep track of the total contribution $\tau_i$ of rows $\phi_r, r \leq i$, to the corresponding $[0, 0, 1, 0, 0]$-admissible partition,

\[ \tau_i = \sum_{r=1}^{i} \sum_{j=1}^{w} f_{rj} n_{rj}. \]

Hence we should record our steps in the construction with data

\[ \phi_0, \phi_1, \ldots, \phi_i; \mu_i; \tau_i; \mu_i \rightsquigarrow \phi_0, \phi_1, \ldots, \phi_i, \phi_i+1; \tau_{i+1}; \mu_{i+1}. \]

Finally, if we are interested only in the number of constructed partitions, and do not need the constructed $[0, 0, 1, 0, 0]$-admissible frequency matrices $\phi_0, \phi_1, \ldots, \phi_i$, we should record our steps in the construction only with data

\[ \tau_i; \mu_i \rightsquigarrow \phi_{i+1}; \tau_{i+1}; \mu_{i+1}, \]

i.e. we should regard the step (5.13) as the map

\[ ((\tau_i, \mu_i), \phi_{i+1}) \mapsto (\tau_{i+1}, \mu_{i+1}), \]

and this is what the Python code 21AAIC.py does in two loops “for total0, ms0 in all total ms0:” and “for fs1 in all fs:” starting at lines 77 and 78. If in 21AAIC.py we change the “While loop” and the “result” into

while True:
    all_total_ms1 = []
    row1 = get_row(i, w)
    all_fs = list(all_frequencies(i, *highest_weight))
    for total0, ms0 in all_total_ms0:
        for fs1 in all_fs:
            ms = filter_frequencies(fs1, ms0, *highest_weight)
            if ms is None:
                continue
            total1 = row_fs_value(row1, fs1) + total0
            all_total_ms1.append((total1, ms))
    if i == N:
        #if i == w//2:
        break
i += 1
all_total_ms0 = all_total_ms1

result = []
for total1, ms1 in all_total_ms1:
    if total1 <= 6:
        result.append(total1)
print(result)

# print(len(all_total_ms1))
then the activated “print(len(all total ms1))” on line 92 shows that there is altogether 164 final pairs \((\tau_5, \mu_5)\) in our construction of \((0, 1, 0)\)-admissible partitions with the support in the first \(N = 5\) rows. If we print only the list of \(\tau_5 \leq 6\) which appear in the final step of (5.12) we get

\[
\text{highest_weight} = [0, 0, 1, 0, 0]
\]

\(k = 1\ \ \ w = 5\)

\([0, 5, 6, 3, 4, 5, 6, 2, 6, 3, 4, 5, 1, 6, 5, 6, 4, 5, 6, 2, 6, 3]\)

From this list we see that \(\tau = 6\) appears 7 times, i.e. there is 7 \((0, 1, 0)\)-admissible partitions of 6. The Python code 21AAIC.py is just a bit faster and more polished version of this code and gives for the number of all \((0, 1, 0)\)-admissible partitions of \(n \leq N = 6\) the list

\[
\text{highest_weight} = [0, 0, 1, 0, 0]
\]

\(k = 1\ \ \ w = 5\)

\([[1, 1], [2, 2], [3, 3], [4, 3], [5, 5], [6, 7]]\)

Of course, this example would have been much shorter if we simply wrote “by hand” all \((0, 1, 0)\)-admissible partitions of \(n \leq 6\), as we did for all \((2, 0, 0)\)-admissible partitions of \(n \leq 8\) in Example 5.3.

**Remark 5.4.** A basis of the finite dimensional representation \(L_{C_\ell}(k_1, \ldots, k_\ell)\) is parametrized in \([FFL]\) in terms of symplectic Dyck paths—this result is closely related to our Conjecture 3.3. For \(\ell = 4\) Feigin-Fourier-Littelmann’s theorem can be rephrased in terms of \((0, k_1, k_2, k_3, k_4))-\text{admissible } 5 \times 9\text{ matrix}\footnotemark[4]

\[
\begin{bmatrix}
  k_0 & 0 & k_1 & 0 & k_2 & 0 & k_3 & 0 & k_4 \\
  k_0 & 0 & k_1 & 0 & k_2 & 0 & k_3 & 0 & \bullet \\
  k_0 & 0 & k_1 & 0 & k_2 & 0 & \bullet & \bullet & \bullet \\
  k_0 & 0 & k_1 & 0 & \bullet & \bullet & \bullet & \bullet & \bullet \\
  k_0 & 0 & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\
\end{bmatrix}
\]

in \([FFL]\) these matrices are written in the form

\[
\begin{bmatrix}
  \bullet & \bullet & \bullet \\
  \bullet & \bullet & \bullet \\
  \bullet & \bullet & \bullet \\
  \bullet & \bullet & \bullet \\
\end{bmatrix}
\]

\footnotetext[4]{Here \(k_0 = 0\), but it works for any \(k_0\) since \(L_{C_\ell}(k_1, \ldots, k_\ell) \subset L_{C_{(1)}}(k_0, k_1, \ldots, k_\ell)\).}

6. **Appendix: Python code for counting admissible colored partitions**

Here we give the Python code which is in part explained in Example 5.3 where diagonals in the array (3.3) became the rows in the matrix (5.12).
The program 21AAIC counts the number \( P(n) \) of \([k_1, k_2, \ldots, k_w]\) -admissible colored partitions of \( n \leq N \) on the array \( N_w \) of \( w \) rows of natural numbers. We input by hand \( N \) and \( k_1, k_2, \ldots, k_w \) as the list 'highest_weight' on line 57. The result is a list of pairs \([n, P(n)]\).

```python
def get_row(i, w):
    return [max(0, x) for x in range(i*2 - 1, i*2 - w - 1, -1)]

def all_subfrequencies(c, r):
    for g0 in range(r + 1):
        if c == 1:
            yield [g0]
        else:
            for gs in all_subfrequencies(c - 1, max(0, r - g0)):
                yield [g0] + gs

def all_frequencies(i, *ks):
    rest = []
    for x in reversed(ks):
        rest.append(x)
    if i > w//2:
        for gs in all_subfrequencies(w, k):
            yield gs
    else:
        for gs in all_subfrequencies(i*2-1, sum(ks[-i*2+1:])):
            yield gs + rest[2 * i-1:]

def filter_frequencies(fs, ms1, *ks):
    k = sum(ks)
    ms = []
    for j, f in enumerate(fs):
        if j:
            m = ms1[j - 1]
            m0 = ms[-1]
            if m0 > m:
                m = m0
            m += f
            if m > k:
                return None
            ms.append(m)
        else:
            ms.append(f)
    return ms

def row_fs_value(row, fs):
    s = 0
```
for v, f in zip(row, fs):
    s += v * f
return s

if __name__ == '__main__':
    """One should put by hand N and the 'highest weight'.
    For w=2n+1 for (k0,k1,...,kn) put [k0,0,k1,0,...,0,0,kn].
    For w=2n for (k0,k1,...,kn)e put [k0,k1,0,...,0,kn].""
    N = 6
    highest_weight = [0, 0, 1, 0, 0]
    print("highest_weight =", highest_weight)
    w = len(highest_weight)
    k = sum(highest_weight)
    print(‘k =’, k, ‘ w =’, w)
    i = 1
    frequencies = {}
    result = []
    ms0 = []
    for j in range(0, len(highest_weight)):
        ms0.append(sum(highest_weight[-j-1:]))
    all_total_ms0 = [(0, ms0)]
    while True:
        all_total_ms1 = []
        row1 = get_row(i, w)
        #print( 'i =', i, 'row1 =', row1)
        min_next_row = get_row(i + 1, w)[-1]
        all_fs = list(all_frequencies(i, *highest_weight))
        #print( 'i =', i, 'all_fs =', all_fs)
        all_total_ms0 = all_total_ms1
        for total0, ms0 in all_total_ms0:
            for fs1 in all_fs:
                ms = filter_frequencies(fs1, ms0, *highest_weight)
                if ms is None:
                    continue
                total1 = row_fs_value(row1, fs1) + total0
                if total1 <= N:
                    if total1 > total0:
                        frequencies[total1] = 1 + frequencies.get(total1, 0)
                    if total1 <= N - min_next_row:
                        all_total_ms1.append((total1, ms))
                    if row1[-2] > 0:
                        result.append([row1[-1], frequencies.get(row1[-1], 0)])
                        result.append([row1[-2], frequencies.get(row1[-2], 0)])
                    if max(row1[-2:]) >= N:
                        break
                i += 1
        all_total_ms0 = all_total_ms1
if w%2 == 0:
    result.remove([0,0])
print(result)

Example 6.1. In the Rogers-Ramanujan case, i.e. for w = 2 and k = 1 we get:

```
[0, 1]
```

```
[1, 1], [2, 1], [3, 1], [4, 2], [5, 2], [6, 3], [7, 3], [8, 4],
[9, 5], [10, 6], [11, 7], [12, 9], [13, 10], [14, 12],
[15, 14], [16, 17], [17, 19], [18, 23], [19, 26], [20, 31];
```

```
[1, 0]
```

```
[1, 0], [2, 1], [3, 1], [4, 1], [5, 1], [6, 2], [7, 2], [8, 3],
[9, 3], [10, 4], [11, 4], [12, 6], [13, 6], [14, 8], [15, 9],
[16, 11], [17, 12], [18, 15], [19, 16], [20, 20].
```

Example 6.2. For \((2,1,0,0,1)^e\)-admissible partitions in Example 4.4 we get:

```
[0, 1, 0, 0, 0, 0, 0, 1]
```

```
[1, 2], [2, 4], [3, 8], [4, 15], [5, 27], [6, 47], [7, 78],
[8, 128], [9, 205], [10, 323], [11, 499], [12, 763],
[13, 1148], [14, 1709], [15, 2516], [16, 3669],
[17, 5297], [18, 7589], [19, 10779], [20, 15204].
```

Example 6.3. Related to Remark 5.4, we can modify slightly the above Python code for calculating dimensions of representations \(L_{\mathcal{C}^e}(k_1, \ldots, k_\ell)\) (one way to do it is to use the change described in Example 5.3, activate “if i == w//2:” on line 82 and “print(len(all total ms1))” on line 92, deactivate “#i if i == N:” on line 81 and set highest weight = \([0,0,1,0,1,0,2,0,2]\) for \(\dim L [1, 1, 2, 2] \) . For example, for \(\ell = 4\) we have:

```
dim L [1, 1, 2, 2] = 3459456,
dim L [2, 1, 2, 2] = 9848916,
dim L [0, 2, 2, 2] = 4321512,
dim L [1, 2, 2, 2] = 16358760,
dim L [2, 2, 2, 2] = 43046721.
```

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References

[AAG] K. Alladi, G. E. Andrews and B. Gordon, Refinements and generalizations of Capparelli’s conjecture on partitions, J. Algebra 174 (1995), 636–658.

[A1] G. E. Andrews, An analytic generalization of the Rogers-Ramanujan identities for odd moduli, Proc. Nat. Acad. Sci. U.S.A. 71 (1974), 4082–4085.

[A2] G. E. Andrews, The theory of partitions, Encyclopedia of Mathematics and Its Applications, Vol. 2, Addison-Wesley, 1976.

[B] M. K. Bos. Coding the principal character formula for affine Kac-Moody Lie algebras, Math. Comp. 72(244) (2003), 2001–2012.

[BJSM] K. Bringmann, C. Jennings-Shaffer and K. Mahlburg, Proofs and reductions of Kanade and Russell partition identities, Journal f¨ur die reine und angewandte Mathematik 766 (2020), 109–135.

[C] S. Capparelli, On some representations of twisted affine Lie algebras and combinatorial identities, J. Algebra 154 (1993), 335–355.

[DK] J. Dousse and I. Konan, Generalisations of Capparelli’s and Primc’s identities, I: Coloured Frobenius partitions and combinatorial proofs, arXiv:1911.13191.

[FKLMM] B. Feigin, R. Kedem, S. Loktev, T. Miwa and E. Mukhin, Combinatorics of the \( \hat{\mathfrak{sl}}_2 \) species of invariants, Transformation Groups 6 (2001), 25–52.

[F] E. Feigin, The PBW filtration, Represent. Theory 13 (2009), 165-181.

[FFL] E. Feigin, G. Fourier and P. Littelmann, PBW filtration and bases for symplectic Lie algebras, International Mathematics Research Notices 24 (2011), 5760–5784.

[G] B. Gordon, A combinatorial generalization of the Rogers-Ramanujan identities, Amer. J. Math. 83 (1961), 393–399.

[K] V. G. Kac, Infinite-dimensional Lie algebras 3rd ed, Cambridge Univ. Press, Cambridge, 1990.

[KR] S. Kanade and M. C. Russell, IdentityFinder and some new identities of Rogers-Ramanujan type, Experimental Mathematics 24 (2015), 419–423.

[L] J. Lepowsky, Lectures on Kac-Moody Lie algebras, Université Paris VI, Spring, 1978.

[LW] J. Lepowsky and R. L. Wilson, The structure of standard modules, I: Universal algebras and the Rogers-Ramanujan identities, Invent. Math. 77 (1984), 199–290; II: The case \( \mathfrak{A}^{(1)}_1 \), principal gradation, Invent. Math. 79 (1985), 417–442.

[MP] A. Meurman and M. Primc, Annihilating fields of standard modules of \( \mathfrak{sl}(2, \mathbb{C}) \) and combinatorial identities, Memoirs of the Amer. Math. Soc. 137, No. 652 (1999).

[P] A. Primc, https://github.com/aprimc/discretaly

[PS1] M. Primc and T. Šišić, Combinatorial bases of basic modules for affine Lie algebras \( C_n^{(1)} \), J. Math. Phys., 57 (2016), 1-19.

[PS2] M. Primc and T. Šišić, Leading terms of relations for standard modules of \( C_n^{(1)} \), The Ramanujan Journal 48 (2019), 509-543.

[T] G. Trupčević, Bases of standard modules for affine Lie algebras of type \( C_\ell^{(1)} \), Communications in Algebra 46 (8) (2018), 3663-3673.