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The module category of the Iwahori-Hecke algebra in non-integral rank

Masaki Mori

Introduction

Throughout this report, we fix a commutative ring $k$ and a parameter $q \in k$. For a natural number $n \in \mathbb{N} = \{0, 1, 2, \ldots \}$, we denote by $H_n = H_n(q)$ the Iwahori–Hecke algebra of type $A_{n-1}$ generated by elements $T_1, T_2, \ldots , T_{n-1}$ with defining relations

$$T_i T_j = T_j T_i \quad \text{if } |i - j| \geq 2, \quad T_i T_{i+1} T_i = T_{i+1} T_i T_{i+1}, \quad (T_i - q)(T_i + 1) = 0.$$ 

Let $\mathfrak{S}_n$ denotes the symmetric group of rank $n$. Then it is known that for each $w \in \mathfrak{S}_n$ with a reduced expression $w = s_{i_1} s_{i_2} \cdots s_{i_r}$ the element $T_w := T_{i_1} T_{i_2} \cdots T_{i_r}$ is well-defined, and that the set $\{T_w \mid w \in \mathfrak{S}_n\}$ forms a basis of $H_n$. Hence it is considered as a $q$-analogue of the symmetric group algebra $k\mathfrak{S}_n$. The Iwahori–Hecke algebra $H_n$ is one of the most important algebra in representation theory. It first comes from a study of flag varieties over the finite fields, and also appears as an endomorphism algebra of a certain representation of the quantum general linear group via an analogue of the Schur–Weyl duality.

Now let $H_n\text{-Mod}$ denotes the (left) module category of $H_n$. In his recent work the author introduce a family of new categories $H_t\text{-Mod}$ indexed by a parameter $t$ which is not necessarily an integer, which “interpolates” ordinary module categories $H_n\text{-Mod}$ for $n \in \mathbb{N}$ in the following sense. First we introduce an index set $B_q(K)$ which contains $\mathbb{N}$ as a subset. An element of $B_q(K)$ is called a $q$-binomial sequence in $k$. Now for a while we assume that $q \in k$ is invertible for simplicity. Then for each $q$-binomial sequence $t \in B_q(k)$, the category $H_t\text{-Mod}$ is defined. We call an object in $H_t\text{-Mod}$ a fakemodule over $H_t$, though “the algebra $H_t$” itself does not really exist. When $t = n \in \mathbb{N}$, there is an equipped functor

$$P: H_n\text{-Mod} \to H_n\text{-Mod}$$

called the realization functor, which sends $H_n$-fakemodules to ordinary $H_n$-modules. This realization functor is full and surjective, so the category $H_n\text{-Mod}$ can be identified with a quotient category of $H_n\text{-Mod}$. The structure of the fakemodule category $H_t\text{-Mod}$ captures a behavior of stable structures of usual $H_n\text{-Mod}$ for $n \gg 0$. It is sometimes simpler than the usual ones, since its hom-spaces almost do not depend on the choice of $t$. Based on this property, its super-version $H_t^{\text{c}}\text{-Mod}$, which is the module category of the Hecke–Clifford superalgebra $H_n^{\text{c}}$ in non-integral rank, is used
by the author [Mor14] to determine the generalized cellular structure of the ordinal module category of $H_n^\ell$.

This work is a part of "representation theory in non-integral rank" developed by Deligne. In his study of tensor categories, he defined the representation category of linear algebraic groups $GL_t$ [DM82, Del90], $O_t$ and $Sp_t$ [Del90], and recently $\mathfrak{S}_t$ [Del07] for the rank $t \in \mathbb{C}$, which is not necessarily an integer. These are symmetric tensor categories which interpolate the ordinal representation categories similarly as described above. Comes and his coauthors study the structures of these categories for $\mathfrak{S}_t$ [CO11, CK12] and $GL_t$ [CW12, Com12] in detail. Recall that the Tannaka–Krein duality allows us to reconstruct an algebraic group from its representation category along with its symmetric tensor structure. In this point of view, by the duality we can regard these tensor categories as generalized groups.

The variations of Deligne’s category are studied in several ways. Knop [Kno06, Kno07] defined a wide generalization of Deligne’s category, which includes ones for the finite general linear groups $GL_t(\mathbb{F}_q)$ and the wreath product $G^t \rtimes \mathfrak{S}_t$ for a finite group $G$. The author [Mor12] also studied the wreath product of algebras as taking the symmetric tensor product $Sym_t(\mathcal{C})$ of a category $\mathcal{C}$. Etingof [Eti14] considered many non-compact tensor products such as degenerate affine Hecke algebras studied by Mathew [Mat13].

Our $H_t$-$Mod$ is considered as a $q$-analogue of the Deligne’s category for $\mathfrak{S}_t$. In fact, when the classical case $q=1$, $H_t$-$Mod$ contains Deligne’s category as a full subcategory. When $k$ is a field of characteristic zero, Deligne’s category consisting of all finitely presented objects in $H_t$-$Mod$. In contrast, in the modular case our $H_t$-$Mod$ has more objects than Deligne’s category.

1. Stable structures of the module category

1.1. Parabolic modules. A composition $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_r)$ of $n \in \mathbb{N}$ is a finite tuple of natural numbers $\lambda_i \in \mathbb{N}$ such that $|\lambda| := \sum \lambda_i = n$. For such $\lambda$, let $H_\lambda \subset H_n$ denotes the corresponding parabolic subalgebra

$$H_\lambda := H_{\lambda_1} \otimes H_{\lambda_2} \otimes \cdots \otimes H_{\lambda_r} \hookrightarrow H_n.$$ 

Let $km_\lambda$ be the trivial module of $H_\lambda$ spanned by $m_\lambda$ on which each $T_w \in H_\lambda$ acts by a scalar $q^{\ell(w)}$. Its induced $H_n$-module

$$M_\lambda := H_n \otimes_{H_\lambda} km_\lambda$$

is called the parabolic module. For example, $1_n := M_{(n)}$ is the trivial module of $H_n$ and $M_{(1^n)} \simeq H_n$ is its left regular representation where $(1^n) := (1, 1, \ldots, 1)$.

To represent elements of these parabolic modules and homomorphisms between them, we here introduce notions on tableaux. As usual, the Young diagram of a composition $\lambda$ is defined by

$$Y(\lambda) := \{(i, j) \mid 1 \leq i, 1 \leq j \leq \lambda_i\}.$$ 

A row-semistandard tableau of shape $\lambda$ is a function $T: Y(\lambda) \rightarrow \{1, 2, \ldots\}$ which satisfies $T(i, j) \leq T(i, j + 1)$ for each pair of adjacent boxes $(i, j), (i, j + 1) \in Y(\lambda)$, that is, entries in each row of $T$ are weakly increasing. The weight of such tableau is a composition $\mu = (\mu_1, \mu_2, \ldots)$ whose $i$-th component is $\mu_i := \#T^{-1}(i)$. We
denote by $\text{Tab}_{\lambda;\mu}$ the set of row-semistandard tableaux of shape $\lambda$ and weight $\mu$. For example,

$$
\text{Tab}_{(2,3);(3,1,0,1)} = \left\{ \begin{array}{c}
1 & 1 \\
2 & 4 \\
1 & 4 \\
1 & 1
\end{array}, \begin{array}{c}
1 & 2 \\
4 & 1 \\
1 & 1 \\
1 & 1
\end{array}, \begin{array}{c}
2 & 4 \\
1 & 1 \\
1 & 2 \\
1 & 1
\end{array} \right\}.
$$

A row-semistandard tableau is called a \textit{row-standard tableau} if its weight is $(1^n)$. We denote by $\text{Tab}_\lambda := \text{Tab}_{\lambda;(1^n)}$ the set of row-standard tableaux of shape $\lambda$.

The $k$-module $M_\lambda$ (resp. $\text{Hom}_{H_n}(M_\mu, M_\lambda)$) has a basis parametrized by the set $\text{Tab}_\lambda$ (resp. $\text{Tab}_{\lambda;\mu}$) described as follows. First for a row-standard tableau $T$, let $d(T) \in \mathfrak{S}_n$ be a permutation obtained by reading its entries from left to right for each rows from top to bottom. For example,

$$
T = \begin{array}{c}
1 & 2 & 4 & 5 \\
3 & 7 & 8 & 6
\end{array}
$$

corresponds to $d(T) = \left( \begin{array}{c}
1 & 2 & 3 & 4 & 5 & 6 & 7 & 8
\end{array} \right) = s_3s_4s_6s_7$.

For each $T \in \text{Tab}_\lambda$, we let $m_T := T_{d(w)} m_\lambda \in M_\lambda$. Then one can prove that the set $
\{ m_T \mid T \in \text{Tab}_\lambda \}$ forms a basis of $M_\lambda$. Suppose each number $i$ is contained in the $r(i)$-th row of $T$. The action of $H_n$ on it is described as

$$
T_i \cdot m_T = \begin{cases}
qm_T & \text{if } r(i) = r(i+1), \\
m_{s_i T} & \text{if } r(i) < r(i+1), \\
qm_T + (q-1)m_{s_i T} & \text{if } r(i) > r(i+1).
\end{cases}
$$

Next take two compositions $\lambda, \mu$ of $n$. For $S \in \text{Tab}_{\lambda;\mu}$, we denote by $\text{Tab}_S$ the set

$$
\{ T \in \text{Tab}_\lambda \mid T\larrow_{\mu} = S \}
$$

where $T\larrow_{\mu}$ is a row-semistandard tableau of weight $\mu$ obtained from $T$ by replacing its entries $1, 2, \ldots, \mu_1$ by $1, \mu_1 + 1, \ldots, \mu_1 + \mu_2$ by $2$, and so forth. For example, for

$$
S = \begin{array}{c}
1 & 1 & 2 & 3 \\
1 & 4 & 4 & \end{array},
$$

we have

$$
\text{Tab}_S = \left\{ \begin{array}{c}
1 & 2 & 4 & 5 \\
3 & 7 & 8 & 6
\end{array}, \begin{array}{c}
1 & 3 & 4 & 5 \\
2 & 3 & 4 & 6
\end{array}, \begin{array}{c}
1 & 2 & 4 & 6 \\
3 & 7 & 8 & 5
\end{array}, \begin{array}{c}
1 & 3 & 4 & 6 \\
2 & 7 & 8 & 5
\end{array}, \begin{array}{c}
2 & 3 & 4 & 6 \\
1 & 7 & 8 & 5
\end{array} \right\}.
$$

Since $M_\mu$ is a cyclic module, an $H_n$-homomorphism $M_\mu \to M_\lambda$ is determined by the value on $m_\mu$. In this point of view, we have an isomorphism

$$
\text{Hom}_{H_n}(M_\mu, M_\lambda) \simeq \{ x \in M_\lambda \mid T_w x = q^{\ell(w)} x \text{ for all } T_w \in H_\mu \}.
$$

The right-hand side has a basis $\{ m_S \mid S \in \text{Tab}_{\lambda;\mu} \}$ where $m_S := \sum_{T \in \text{Tab}_S} m_T$. When there are no risks of confusions, we denote by the same symbol $m_S$ the corresponding $H_n$-homomorphism $M_\mu \to M_\lambda$.

\subsection{Induced modules.} The direct sum category $\bigoplus_n (H_n\text{-Mod})$ has the structure of tensor category by the convolution product $\ast$ defined as

$$
V \ast W := H_{m+n} \otimes_{H_{(m,n)}} (V \otimes W) \in H_{m+n}\text{-Mod}
$$

for $V \in H_m\text{-Mod}$ and $W \in H_n\text{-Mod}$, where $\otimes$ denotes the outer tensor product of modules. For example, for a composition $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_r)$ the parabolic module $M_\lambda$ can be expressed as

$$
M_\lambda \simeq 1_{\lambda_1} \ast 1_{\lambda_2} \ast \cdots \ast 1_{\lambda_r}.
$$
We define the induction functor as taking convolution with the trivial module. It plays a central role in what follows.

**Definition 1.1.** Let \( k, n \in \mathbb{N} \). For an \( H_n \)-module \( V \), we denote by \( \text{Ind}_k V \) the \( H_{k+n} \)-module
\[
\text{Ind}_k V := 1_k \ast V.
\]
This defines a functor \( \text{Ind}_k : H_n \text{-Mod} \to H_{k+n} \text{-Mod} \) between module categories.

Since the action \( H_{k+n} \otimes H_{(k,n)} \) is free, it follows that the functor \( \text{Ind}_k \) is exact. More strongly we can prove that this functor has both left and right adjoint.

**Definition 1.2.** Let \( k, n \in \mathbb{N} \). For an \( H_{k+n} \)-module \( W \), we define \( H_n \)-modules
\[
\text{Res}_k W := \text{Hom}_{H_{(k,n)}}(1_k \otimes H_n, W|_{(k,n)})
\]
\[
\simeq \{ x \in W | T_i x = qx \text{ for } 1 \leq i \leq k \},
\]
\[
\text{Res}'_k W := (H_n \otimes 1_k) \otimes_{H_{(n,k)}} W|_{(n,k)}
\]
\[
\simeq W/\sim, \text{ where } T_i x \sim qx \text{ for } n + 1 \leq i \leq n + k.
\]
where we denote by \( W|_\lambda \) the restricted \( H_\lambda \)-module. \( \text{Res}_k \) and \( \text{Res}'_k \) are functors \( H_{k+n} \text{-Mod} \to H_n \text{-Mod} \).

**Proposition 1.3.** \( \text{Res}_k \) (resp. \( \text{Res}'_k \)) is a right (resp. left) adjoint of \( \text{Ind}_k \).

Now for a convention, we let \( H_n \text{-Mod} := \{ 0 \} \) for \( n \in \mathbb{Z} \) such that \( n < 0 \). We also extend the definitions of the functors above for \( k, n \in \mathbb{Z} \) so that these are zero when the condition \( k, n \geq 0 \) is not satisfied. For two induced modules, we can describe the set of homomorphisms between them as follows.

**Theorem 1.4.** Let \( d, m, n \in \mathbb{N} \) such that \( m, n \leq d \). For each \( V \in H_m \text{-Mod} \) and \( W \in H_n \text{-Mod} \), there is an isomorphism of \( k \)-modules
\[
\text{Hom}_{H_d}(\text{Ind}_{d-m} V, \text{Ind}_{d-n} W) \simeq \bigoplus_{m+n-d \leq i} \text{Hom}_{H_i}(\text{Res}'_{m-i} V, \text{Res}_{n-i} W)
\]

natural in \( V \) and \( W \).

The summand in the right-hand side above is zero unless \( 0 \leq i \leq m, n \). In particular, as we varies the rank \( d \in \mathbb{N} \) larger, this set is stable for \( d \geq m + n \). This phenomenon suggests us that there should be a category which covers \( H_d \text{-Mod} \) and has the hom-sets in the form
\[
\bigoplus_i \text{Hom}_{H_i}(\text{Res}'_{m-i} V, \text{Res}_{n-i} W),
\]
the stable set which does not depend on \( d \). We realize this imaginary category as \( H_d \text{-Mod} \), the category of fakemodules, in the next section.

Note that a parabolic module \( M_\lambda \) is a special case of induced modules, that is, we can write \( M_\lambda \simeq \text{Ind}_\lambda M_{\lambda'} \) where \( \lambda' = (\lambda_2, \ldots, \lambda_r) \). Taking \( d \gg 0 \) corresponds to considering Young diagrams whose first rows are very long:

\[
\begin{array}{cccccccc}
\vdots
\end{array}
\]

The theorem says that the structure of the module category will be stable for such Young diagrams with sufficiently long first rows.
1.3. String diagrams. In order to explain the isomorphism in Theorem 1.4 precisely, we introduce string diagrams which are useful for calculation in theory of 2-categories. In a diagram we visualize a functor by a colored string. The right (resp. left) region separated by a string stands for the domain (resp. codomain) category of the corresponding functor. A composite of these functors is represented by a sequence of strings arranged horizontally. In particular, the identity functor is represented by the "no strings" diagram. A natural transformation between such functors are represented by a figure connecting these sequences from top to bottom.

In this report, we represent the functor \( \text{Ind}_k \) by a down arrow \( \downarrow \), and both \( \text{Res}_k \), \( \text{Res}'_k \) by up arrows \( \uparrow \) which are labeled by \( k \). For example, \( f: \text{Ind}_3 \text{Res}_6 \rightarrow \text{Res}_4 \text{Res}_1 \text{Ind}_2 \) is represented by a figure like

\[
\begin{array}{c}
\text{3} \\
\downarrow \quad f \\
\text{4} \\
\end{array}
\]

Note that the diagram above can not distinguish \( \text{Res}_k \) from \( \text{Res}'_k \), but we only use diagrams when it is clear from the context.

The adjointness between \( \text{Ind}_k \) and \( \text{Res}_k \) yields natural transformations

\[
\delta_k: \text{Id} \rightarrow \text{Res}_k \text{Ind}_k, \quad \epsilon_k: \text{Ind}_k \text{Res}_k \rightarrow \text{Id}
\]
called the unit and the counit respectively. We represent these morphisms by the cap and the cup diagrams:

\[
\delta_k = \begin{array}{c} \text{k} \\
\cap \\
\end{array}, \quad \epsilon_k = \begin{array}{c} \text{k} \\
\cup \\
\end{array}.
\]

We also have the the unit \( \delta'_k: \text{Id} \rightarrow \text{Ind}_k \text{Res}'_k \) counit \( \epsilon'_k: \text{Res}'_k \text{Ind}_k \rightarrow \text{Id} \) induced by the other adjunction. We represent them by the same diagrams as above but arrows are reversed:

\[
\delta'_k = \begin{array}{c} \text{k} \\
\cap \\
\end{array}, \quad \epsilon'_k = \begin{array}{c} \text{k} \\
\cup \\
\end{array}.
\]

Now let \( k, l \in \mathbb{N} \). We define three \( H_{k+l} \)-homomorphisms

\[
\mu_{(k,l)}: M_{(k,l)} \rightarrow 1_{k+l}, \quad \Delta_{(k,l)}: 1_{k+l} \rightarrow M_{(k,l)}, \quad \sigma_{(k,l)}: M_{(l,k)} \rightarrow M_{(k,l)}
\]
which correspond to the row-semistandard tableaux

\[
\begin{array}{c} 11\ldots1112|2|2|2 \\
|11|11|11|11|11|11|
\end{array}, \quad \begin{array}{c} 22\ldots22222 \\
|11|11|11|11|11|11|
\end{array}
\]
respectively. These homomorphisms induce natural transformations between functors \( H_{n}-\text{Mod} \rightarrow H_{k+l+n}-\text{Mod} \),

\[
\mu_{(k,l)}: \text{Ind}_k \text{Ind}_l \rightarrow \text{Ind}_{k+l}, \quad \Delta_{(k,l)}: \text{Ind}_{k+l} \rightarrow \text{Ind}_k \text{Ind}_l, \quad \sigma_{(k,l)}: \text{Ind}_k \text{Ind}_l \rightarrow \text{Ind}_k \text{Ind}_l
\]
which we denote by the same symbols. Again, if \( k \) and \( l \) do not satisfy \( k, l \geq 0 \), then these morphisms are defined to be zero. We represent these natural transformations
by the string diagrams
\[\mu(k,l) = \quad \Delta(k,l) = \quad \sigma(k,l) = ,\]
that is, junction, branch, and crossing of strings respectively. Finally, an obvious isomorphism \(\text{Ind}_0 \simeq \text{Id}\) and its inverse are represented by broken strings:
\[
\begin{array}{c}
\text{0} \\
\Downarrow \quad \Downarrow
\end{array}
\quad \quad \quad 
\begin{array}{c}
\text{0} \\
\Uparrow \quad \Uparrow
\end{array}
\]

Now the isomorphism in Theorem 1.4 can be represented as follows. For an \(H_t\)-homomorphism \(f: \text{Res}_{m-i}'V \rightarrow \text{Res}_{n-i}W\) in the right-hand side, the corresponding \(H_d\)-homomorphism \(\text{Ind}_{d-m}V \rightarrow \text{Ind}_{d-n}W\) can be illustrated as
\[
\begin{array}{c}
d-m \\
\downarrow
\end{array}
\quad f
\begin{array}{c}
m-i \\
\downarrow
\end{array}
\quad \begin{array}{c}
d-m-n+i \\
\downarrow
\end{array}
\quad \begin{array}{c}
n-i \\
\downarrow
\end{array}
\quad \begin{array}{c}
d-n \\
\downarrow
\end{array}
\quad \begin{array}{c}
V \\
\downarrow
\end{array}
\quad W
\]
The theorem follows by studying the double cosets \(\mathfrak{S}_{(d-m,m)} \cap \mathfrak{S}_n \wedge \mathfrak{S}_{(d-n,n)}\).

2. The category of fakemodules

2.1. Binomial sequences. Before we proceed to the main definition, we need to explain the index set \(B_q(k)\) of \(q\)-binomial sequences. The key point of our theory is that the composition of certain \(H_n\)-homomorphism can be computed by \(q\)-binomial coefficients. Here a \(q\)-binomial coefficient \(\binom{n}{k}\) for \(n, k \in \mathbb{N}\) is defined as
\[
\binom{n}{k} := \frac{[n][n-1] \cdots [n-k+1]}{[1][2] \cdots [k]} = \frac{[n]!}{[k]![n-k]!}
\]
where \([i] := 1 + q + \cdots + q^{i-1}\) is the \(q\)-integer and \([i]! := [1][2] \cdots [i]\) is the \(q\)-factorial. This rational function for the variable \(q\) actually is in the polynomial ring \(\mathbb{Z}[q]\), so assigning the actual value of \(q \in k\) we can regard \(\binom{n}{k} \in k\). A \(q\)-binomial sequence is a generalization of the function \(N \rightarrow k; k \mapsto \binom{n}{k}\) for \(n \in \mathbb{N}\).

**Definition 2.1.** A \(q\)-binomial sequence in \(k\) is a function \(t: N \rightarrow k\), whose values are written as \(k \mapsto \binom{t}{k}\), which satisfies
\[
\binom{0}{0} = 1 \quad \text{and} \quad \binom{t}{k} \binom{t}{l} = \sum_{0 \leq i \leq k,l} q^{(k-i)(l-i)} \binom{l}{i} \binom{k+l-i}{k+l} \binom{t}{k+l-i}.
\]
We denote by \(B_q(k)\) the set of all \(q\)-binomial sequences in \(k\).

When \(q = 1\), a 1-binomial coefficient \(\binom{n}{k}\) is just the ordinary binomial coefficient \(\binom{n}{k}\). So we prefer writing a value of 1-binomial sequence as \((\binom{t}{k})\) rather than \(\binom{t}{k}\).

As described above, each natural number defines a \(q\)-binomial sequence. Namely:

**Lemma 2.2.** For each \(n \in \mathbb{N}\), the function \(k \mapsto \binom{n}{k}\) is a \(q\)-binomial sequence. Moreover, the map \(N \rightarrow B_q(k)\) is injective.
Henceforth we regard $\mathbb{N}$ as a subset of $B_{q}(k)$ via this embedding. Interestingly the addition on $\mathbb{N}$ can be lifted to the whole set $B_{q}(k)$ as follows, which makes it into a commutative monoid.

PROPOSITION 2.3. For two $q$-binomial sequences $t$ and $u$, let

$$
\begin{bmatrix}
t + u \\
k
\end{bmatrix} := \sum_{0 \leq i \leq k} q^{(i)} (q - 1)^i [i!] \sum_{0 \leq j \leq k-i} \begin{bmatrix}
k - j \\
i
\end{bmatrix} \begin{bmatrix}
i + j \\
k - j
\end{bmatrix} \begin{bmatrix}
t \\
i + j
\end{bmatrix} \begin{bmatrix}
u \\
k
\end{bmatrix}.
$$

Then $t + u$ is also a $q$-binomial sequence. $B_{q}(k)$ forms a commutative monoid with respect to this addition and the unit element $0$.

Now in the examples below we assume that $k$ is a field. We here give the complete classification of $q$-binomial sequences under this assumption. Let $e := \text{char}_{q} k$ be the $q$-characteristic of $k$, the minimum positive number such that $[e] = 0$. When there are no such numbers we let $e = 0$ for convention.

EXAMPLE 2.4. When $q = 0$, we have $B_{0}(k) = \mathbb{N} \cup \{\infty\}$. Here $\infty$ is a $q$-binomial sequence which satisfy $\infty + t = \infty$ for all $t \in B_{q}(k)$ defined by

$$
\begin{bmatrix}
\infty \\
k
\end{bmatrix} := \frac{1}{(1-q)(1-q^2) \cdots (1-q^k)}
$$

when $1 - q^i (i \geq 1)$ are all invertible. In this case we have just $[\infty] = 1$ for all $k$.

EXAMPLE 2.5. Suppose $q \neq 0$ and $e = 0$. Then the map

$$
B_{q}(k) \rightarrow k \\
t \mapsto [t]
$$

where $[t] := [\begin{bmatrix} t \end{bmatrix}]$ is bijective. For each $x \in k$, the corresponding $t \in B_{q}(k)$ such that $x = [t]$ is given by

$$
\begin{bmatrix}
t \\
k
\end{bmatrix} := q^{(i)} \frac{x(x - [1]) \cdots (x - [k-1])}{[1][2] \cdots [k]} .
$$

Beware that this bijection does not preserve addition unless $q = 1$.

EXAMPLE 2.6. When $e > 0$, there is an exact sequence of commutative monoids

$$
0 \rightarrow B_{1}(k) \rightarrow B_{q}(k) \rightarrow \mathbb{Z}/e\mathbb{Z} \rightarrow 0.
$$

Moreover if $q = 1$ (i.e. $e = \text{char} k > 0$) naturally $B_{1}(k) = \mathbb{Z}_{e}$, the set of $e$-adic integers. In this case the values for $n \in \mathbb{Z}_{e}$ is given by

$$
\begin{bmatrix}
n \\
k
\end{bmatrix} := \left(\begin{array}{l}n \mod e^k \\
k
\end{array}\right)
$$

which is well-defined modulo $e$ by Lucas's theorem.

We will use such a $q$-binomial sequence $t$ to specify the "rank" of the "Iwahori-Hecke algebra $\underline{H}_{t}$". However, in the following construction of its fakemodule category, we will need to use $q$-binomial sequences "$t - m$" for all $m \in \mathbb{N}$. Its uniqueness is guaranteed by the next lemma, while its existence is not in general.

LEMMA 2.7. The shift map $B_{q}(k) \rightarrow B_{q}(k); t \mapsto t + 1$ is injective. It is also surjective if and only if $q \in k$ is invertible.
Hence we have to use \( q \)-binomial sequences only which have following property:

**Definition 2.8.** A \( q \)-binomial sequence \( t \) in \( \k \) is said to be total if \( t - m \) exists for all \( m \in \mathbb{N} \). We denote by \( B^+_q(\k) \) the set of total \( q \)-binomial sequences; so

\[
B^+_q(\k) := \bigcap_{m \in \mathbb{N}} (B_q(\k) + m).
\]

The subset \( B^+_q(\k) \) is an ideal of \( B_q(\k) \) with respect to the addition. As we noted above, if \( q \) is invertible then \( B^+_q(\k) = B_q(\k) \). On the other hand, for \( q = 0 \) we have just \( B^+_0(\k) = \{\infty\} \).

**2.2. The category of induced fakemodules.** Now let \( t \in B^+_q(\k) \) be a total \( q \)-binomial sequence in \( \k \). In order to define the whole category \( H_t^-\text{Mod} \), we first need to introduce its full subcategory \( H_t^-\text{Mod}_0 \). An object of \( H_t^-\text{Mod}_0 \) is written as \( \text{Ind}_{t-m}V \), and called an induced fakemodule. It is made to imitate the behaviors of the ordinary induced module \( \text{Ind}_{d-m}V \) which we introduced in the previous section. We define the category \( H_t^-\text{Mod}_0 \) in terms of generators and relations as follows.

**Definition 2.9.** An object in the category \( H_t^-\text{Mod}_0 \) is an \( H_m \)-module \( V \) for some \( m \in \mathbb{N} \), represented by the symbol \( \text{Ind}_{t-m}V \). Morphisms between these objects are generated by

\[
\text{Ind}_{t-m}f: \text{Ind}_{t-m}V \to \text{Ind}_{t-m}W,
\]

defined for each \( H_m \)-homomorphism \( f: V \to W \), and

\[
\mu(t-m-k,k)V: \text{Ind}_{t-m-k}\text{Ind}_kV \to \text{Ind}_{t-m}V,
\]

\[
\Delta(t-m-k,k)V: \text{Ind}_{t-m}V \to \text{Ind}_{t-m-k}\text{Ind}_kV
\]

defined for each \( H_m \)-module \( V \) and \( k \in \mathbb{N} \), with relations listed below. The first two of them are:

(a) \( \text{Ind}_{t-m} \) is a \( \k \)-linear functor \( H_m^-\text{Mod} \to H_t^-\text{Mod} \). That is,

\[
\text{Ind}_{t-m}\text{id}_V = \text{id}_{\text{Ind}_{t-m}V}, \quad \text{Ind}_{t-m}(f \circ g) = \text{Ind}_{t-m}f \circ \text{Ind}_{t-m}g
\]

and

\[
\text{Ind}_{t-m}(af + bg) = a \cdot \text{Ind}_{t-m}f + b \cdot \text{Ind}_{t-m}g
\]

for suitable \( H_m \)-homomorphisms \( f, g \) and scalars \( a, b \in \k \).

(b) \( \mu(t-m-k,k) \) and \( \Delta(t-m-k,k) \) are both natural transformations between functors \( H_m^-\text{Mod} \to H_t^-\text{Mod} \), respectively \( \text{Ind}_{t-m-k}\text{Ind}_k \) and \( \text{Ind}_{t-m} \). That is, the square below and its dual commute for any \( H_m \)-homomorphism \( f: V \to W \):

\[
\begin{array}{ccc}
\text{Ind}_{t-m-k}\text{Ind}_kV \xrightarrow{\mu(t-m-k,k)V} & \text{Ind}_{t-m}V \\
\text{Ind}_{t-m-k}\text{Ind}_kf \downarrow & & \downarrow \text{Ind}_{t-m}f \\
\text{Ind}_{t-m-k}\text{Ind}_kW \xrightarrow{\mu(t-m-k,k)W} & \text{Ind}_{t-m}W.
\end{array}
\]

The rest relations are represented by diagrams as we do before. To represent the functor \( \text{Ind} \) and the natural transformations \( \mu \) and \( \Delta \), we use same diagrams as \( \text{Ind} \), \( \mu \) and \( \Delta \). Here arrows which represent \( \text{Ind} \) always appear in leftmost of each diagram.
(1) The associativity and the coassociativity laws:

\[
\begin{array}{c}
\text{\ associativity law} \\
\text{\ coassociativity law}
\end{array}
\]

(2) The unit and the counit laws:

\[
\begin{array}{c}
\text{\ unit law} \\
\text{\ counit law}
\end{array}
\]

(3) The graded bialgebra relation:

\[
\begin{array}{c}
\text{\ graded bialgebra relation}
\end{array}
\]

(4) The bubble elimination:

\[
\begin{array}{c}
\text{\ bubble elimination}
\end{array}
\]

As we mentioned above, an object and a morphism in \( \underline{H}_{t}\)-\text{Mod} is called an \( \underline{H}_{t}\)-fakemodule and an \( \underline{H}_{t}\)-fakemorphism respectively. We denote by \( \text{Hom}_{\underline{H}_{t}} \) the set of fakemorphisms between fakemodules instead of \( \text{Hom}_{\underline{H}_{t}-\text{Mod}_{0}} \) for simplicity.

When the rank \( t \) is an usual integral rank \( d \in \mathbb{N} \), the relations above are easily verified. Hence there is a canonical functor \( P: \underline{H}_{t}\)-\text{Mod}_{0} \rightarrow \text{H}_{d}\)-\text{Mod} which sends \( \text{Ind}_{d-m} \) to \( \text{Ind}_{d-m} \), \( \mu_{(d-m-k,k)} \) to \( \mu_{(d-m-k,k)} \) and \( \Delta_{(d-m-k,k)} \) to \( \Delta_{(d-m-k,k)} \). We call it the realization functor which realize a module from a fakemodule. Note that we have a natural isomorphism \( \text{Ind}_{0}V \cong V \), and \( \text{Ind}_{0}f = f \) for \( f: V \rightarrow W \) via this isomorphism. The category \( \underline{H}_{t}\)-\text{Mod}_{0} \) has the corresponding object \( \text{Ind}_{0}V \) and the morphism \( \text{Ind}_{0}f \) so that the functor \( P \) is full and surjective. However, in the definition we use values of \( q \)-binomial coefficients \( \left[ \begin{array}{c} d-m \\ k \end{array} \right] \) for negative integers. So in order to define \( \underline{H}_{t}\)-\text{Mod}_{0} \) we must have that the \( q \)-binomial sequence \( d \) is total, or equivalently, \( q \in \mathbb{k} \) is invertible. Summarizing the above:

**Proposition 2.10.** Suppose that \( q \in \mathbb{k} \) is invertible. Then for each \( d \in \mathbb{N} \), there is a full and surjective functor \( P: \underline{H}_{t}\)-\text{Mod}_{0} \rightarrow \text{H}_{d}\)-\text{Mod} such that \( P \text{Ind}_{d-m} = \text{Ind}_{d-m}, P\mu_{(d-m-k,k)} = \mu_{(d-m-k,k)} \) and \( P\Delta_{(d-m-k,k)} = \Delta_{(d-m-k,k)} \).

We remark that if \( m > d \) then a module \( \text{Ind}_{d-m}V \) is zero by definition while the corresponding fakemodule \( \text{Ind}_{d-m}V \) is not. Actually, the kernel of the realization \( P \) is generated by such fakemodules.

As we claimed before, we can completely describe the set of fakemorphisms in \( \underline{H}_{t}\)-\text{Mod}_{0} \) as follows.

**Theorem 2.11.** For \( V \in \text{H}_{m}\)-\text{Mod} and \( W \in \text{H}_{n}\)-\text{Mod}, we have

\[
\text{Hom}_{\underline{H}_{t}}(\text{Ind}_{d-m}V, \text{Ind}_{d-n}W) \cong \bigoplus_{i} \text{Hom}_{\underline{H}_{t}}(\text{Res}_{m-i}V, \text{Res}_{n-i}W).
\]

This isomorphism is defined similarly as in Theorem 1.4 using \( \Delta \) and \( \mu \) instead of \( \Delta \) and \( \mu \) according to the string diagram in §1.3.
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From this result immediately we obtain the statement below.

**Corollary 2.12.** Suppose $q$ is invertible and let $d \in \mathbb{N}$. For $V \in H_m\text{-Mod}$ and $W \in H_n\text{-Mod}$, the realization on the morphisms

$$\text{Hom}_{H_d}(\text{Ind}_{d-m}V, \text{Ind}_{d-n}W) \to \text{Hom}_{H_d}(\text{Ind}_{d-m}V, \text{Ind}_{d-n}W)$$

is an isomorphism when $d \geq m + n$.

The fakemodule category has more morphisms than the ordinal module category, which is usually hidden from our view.

### 2.3. Parabolic fakemodules.
Recall that induction is taking convolution product with the trivial module. By the definition of the category, we can define convolution product of a fakemodule and a usual module as

$$(\text{Ind}_{d-m}V) \ast W := \text{Ind}_{d-m}(V \ast W)$$

for each $V \in H_m\text{-Mod}$ and $W \in H_n\text{-Mod}$. It defines a functor

$$\ast : H_r\text{-Mod}_0 \times H_n\text{-Mod} \to H_{r+n}\text{-Mod}_0.$$

We denote by $\underline{1}_t$ the trivial fakemodule $\text{Ind}_{d}\underline{1}_0$. Then an induced fakemodule can be also written as $\text{Ind}_{d-m}V \simeq \underline{1}_{t-m} \ast V$ using the convolution. This product is also associative, so it provides a structure of right $\bigoplus_n(H_n\text{-Mod})$-module for the category $H_{t+n}\text{-Mod}_0$.

Recall again that a parabolic module $M_\lambda$ is a special case of an induced module. We here introduce parabolic fakemodules into our category $H_r\text{-Mod}_0$ by imitating this construction.

**Definition 2.13.** Let $t$ be a total $q$-binomial sequence. A fakecomposition $\lambda = (\lambda_1, \lambda')$ of $t$ is a pair of a total $q$-binomial sequence $\lambda_1$ and a composition $\lambda'$ such that $|\lambda| := \lambda_1 + |\lambda'| = t$. For such $\lambda$, we write $\lambda = (\lambda_1, \lambda_2, \lambda_3, \ldots)$ where $\lambda_i := \lambda'_{i-1}$ for $i \geq 2$. Let $M_\lambda \in H_{t}\text{-Mod}_0$ be a fakemodule defined by

$$M_\lambda := \text{Ind}_{\lambda_1}M_{\lambda'} \simeq \underline{1}_{\lambda_1} \ast \underline{1}_{\lambda_2} \ast \underline{1}_{\lambda_3} \ast \cdots \ast \underline{1}_{\lambda_l}.$$

Let $\lambda$ and $\mu$ be two fakecompositions of $t$. Let $\lambda|_{d}$ and $\mu|_{d}$ be corresponding fakecompositions of $d \in \mathbb{N}$ obtained by replacing their first components. By Theorem 2.11 the set of $H_d$-homomorphisms $M_{\mu|_{d}} \to M_{\lambda|_{d}}$ stabilizes for sufficiently large $d$ into the set of $H_r$-fakemorphisms $M_{\mu} \to M_{\lambda}$. So as a basis of $\text{Hom}_{H_d}(M_{\mu}, M_{\lambda})$ we can take the set $\text{Tab}_{\lambda|_{d}, \mu|_{d}}$ for $d \gg 0$ which converges to a finite set. Formally we define

$$\text{Tab}_{\lambda, \mu} := \lim_{d} \text{Tab}_{\lambda|_{d}, \mu|_{d}}$$

where the map $\text{Tab}_{\lambda|_{d}, \mu|_{d}} \to \text{Tab}_{\lambda|_{d+1}, \mu|_{d+1}}$ is inserting $\underline{1}$ on the first row of the tableau from left. For example, when $\lambda = (t - 2, 2)$ and $\mu = (t - 3, 2, 1)$, the set $\text{Tab}_{(t-2,2),(t-3,2,1)}$ consisting of the tableaux

$$\begin{array}{cccc}
1 & 1 & \cdots & 1 & 1 & 1 & 2 \\
2 & 3 & & & & & \\
\end{array}, \quad \begin{array}{cccc}
1 & 1 & \cdots & 1 & 1 & 1 & 3 \\
2 & 2 & & & & & \\
\end{array}, \quad \begin{array}{cccc}
1 & 1 & \cdots & 1 & 1 & 2 & 2 \\
1 & 1 & & & & & \\
\end{array}, \quad \begin{array}{cccc}
1 & 1 & \cdots & 1 & 2 & 2 & 3 \\
1 & 1 & & & & & \\
\end{array}, \quad \begin{array}{cccc}
1 & 1 & \cdots & 1 & 1 & 2 & 2 \\
1 & 1 & & & & & \\
\end{array}. \quad \begin{array}{cccc}
1 & 1 & \cdots & 1 & 1 & 2 & 2 \\
1 & 3 & & & & & \\
\end{array}$$
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regardless of \( t \). We denote by the symbol \( m_S \) the fakemorphism \( M_\mu \to M_\lambda \) corresponding to \( S \), so that the set \( \{m_S \mid S \in \text{Tab}_{\lambda \mu} \} \) is a basis of \( \text{Hom}_{H_d}(M_\mu, M_\lambda) \). We can also compute the composition of such fakemorphisms by regarding \( t \) as a large number.

When \( q \) is invertible, for a fakecomposition \( \lambda \) of \( d \in \mathbb{N} \) the realization functor \( P \) sends the fakemodule \( M_\lambda \) to \( M_\lambda \) if \( \lambda \) is a composition (that is, \( \lambda_1 \geq 0 \) and otherwise 0. For two compositions \( \lambda \) and \( \mu \), the realization of fakemorphisms is given by

\[
P: \text{Hom}_{H_d}(M_\mu, M_\lambda) \to \text{Hom}_{H_d}(M_\mu, M_\lambda)
\]

\[
m_S \mapsto \begin{cases} m_S & \text{if } S \in \text{Tab}_{\lambda \mu}, \\ 0 & \text{otherwise.} \end{cases}
\]

More precisely, to realize the \( H_d \)-fakemorphism \( m_S \) to an \( H_d \)-homomorphism \( m_S \), we should cut off superfluous \( [1] \)'s in the first row of \( S \). When there are not enough such \( [1] \)'s, it produces a zero homomorphism. If \( t = 4 \) in the example above, the realization map for \( \lambda = (2, 2) \) and \( \mu = (1, 2, 1) \) is given by

\[
\begin{array}{ccc}
1 & 1 & 1 \to 1 & 1 & 2 & 0 \\
2 & 3 & & 2 & 3
\end{array}
\]

\[
\begin{array}{ccc}
1 & 1 & 1 \to 1 & 1 & 3 & 1 \\
2 & 2 & & 2 & 2
\end{array}
\]

\[
\begin{array}{ccc}
1 & 1 & 1 \to 1 & 1 & 2 & 2 \\
1 & 3 & & 1 & 3
\end{array}
\]

\[
\begin{array}{ccc}
1 & 1 & 1 \to 1 & 1 & 2 & 3 \\
1 & 2 & & 1 & 2
\end{array}
\]

where we represent morphisms \( m_S \) and \( m_S \) by a tableau \( S \) itself for short.

2.4. Completion of category. Unfortunately, the category \( H_t\text{-Mod}_0 \) lacks the ability to apply various categorical operations. We here see that the category \( H_t\text{-Mod}_0 \) can be naturally embedded to a larger category \( H_t\text{-Mod} \) which admits several operations. The category \( H_t\text{-Mod} \) is constructed from \( H_t\text{-Mod}_0 \) using the process of two completions of category, namely pseudo-abelian envelope (see [Del07, §1]) and indization (see [KS06, §6]).

DEFINITION 2.14. Let \( H_t\text{-mod}_0 \) be the full subcategory of \( H_t\text{-Mod}_0 \) consisting of objects \( \text{Ind}_{t \leftarrow m} V \) such that \( V \) is finitely presented. Then we put

\[
H_t\text{-mod} := (H_t\text{-mod}_0)^{\text{psab}},
\]

the pseudo-abelian envelope of the category \( H_t\text{-mod}_0 \). That is, an object in \( H_t\text{-mod} \) is a direct summand of a formal direct sum of objects in \( H_t\text{-mod}_0 \).

\( H_t\text{-mod}_0 \) is considered as the “category of finitely presented \( H_t \)-fakemodules”. Note that it contains all parabolic fakemodules \( M_\lambda \). Recall that for an algebra \( A \), any \( A \)-module is a direct limit (i.e. filtered colimit) of finitely presented ones. Based on this observation, we introduce the definition of the whole fakemodule category \( H_t\text{-Mod} \) as follows.

DEFINITION 2.15. Let

\[
H_t\text{-Mod} := (H_t\text{-mod})^{\text{ind}}
\]

be the indization of the category \( H_t\text{-mod} \). That is, an object in \( H_t\text{-Mod} \) is a formal direct limit (ind-object) of objects in \( H_t\text{-mod} \).
Now it follows by definition.

**Proposition 2.16.** The category $H_t\text{-}\text{Mod}$ is closed under taking direct sums, direct summands and direct limits. $H_t\text{-}\text{mod}$ is a full subcategory of $H_t\text{-}\text{Mod}$ consisting of finitely presented (or compact) objects.

We define the embedding functor $H_t\text{-}\text{Mod}_0 \to H_t\text{-}\text{Mod}$ as follows. Recall that an object in $H_t\text{-}\text{Mod}_0$ is the induced fakemodule $\text{Ind}_{\sim}V$ of an arbitrary $H_m\text{-}\text{module}$ $V$. We can represent $V$ as a direct limit of finitely presented modules $V \simeq \varinjlim V_i$. Via the embedding, the object $\text{Ind}_{\sim}V \in H_t\text{-}\text{Mod}_0$ is mapped to the direct limit $\varinjlim (\text{Ind}_{\sim}V_i) \in H_t\text{-}\text{Mod}$ of finitely presented fakemodules. Then one can prove the following.

**Proposition 2.17.** The functor $H_t\text{-}\text{Mod}_0 \to H_t\text{-}\text{Mod}$ is well-defined and fully faithful.

We still have the realization $P: H_d\text{-}\text{Mod} \to H_d\text{-}\text{Mod}$ for $d \in \mathbb{N}$, and similarly several functors $H_t\text{-}\text{Mod}_0 \to \mathcal{C}$ can be extended to $H_t\text{-}\text{Mod} \to \mathcal{C}$.

### 2.5. Comparison with Deligne’s category

Now assume the classical case $q = 1$, so in particular every 1-binomial sequence is total. Since in this case we have an isomorphism $H_n \simeq k\mathfrak{S}_n$, it seems better to denote our category by $k\mathfrak{S}_t\text{-}\text{Mod}$ rather than $H_t\text{-}\text{Mod}$. Recall that $k\mathfrak{S}_n\text{-}\text{Mod}$ has a tensor product of modules over $k$, defined through the diagonal embedding $\mathfrak{S}_n \hookrightarrow \mathfrak{S}_n \times \mathfrak{S}_n$. We can lift this tensor product on the fakemodule category $k\mathfrak{S}_t\text{-}\text{Mod}$.

**Theorem 2.18.** $k\mathfrak{S}_t\text{-}\text{Mod}$ has a canonical structure of tensor category such that for each $d \in \mathbb{N}$ the realization

$$P: k\mathfrak{S}_d\text{-}\text{Mod} \to k\mathfrak{S}_d\text{-}\text{Mod}$$

is a tensor functor.

We finish this report by describing the relation between the motivating Deligne’s category $[\text{Del}07]$ and $k\mathfrak{S}_t\text{-}\text{Mod}$. For $t \in B_1(k)$, let $\text{Rep}(\mathfrak{S}_t)$ denotes the Deligne’s category for the rank $(1^t)$ in $k$. It has an object $[m] \in \text{Rep}(\mathfrak{S}_t)$ for each $m \in \mathbb{N}$ which correspond to the parabolic fakemodule $M_{(t-m,1^m)}$ in our notation, and $\text{Rep}(\mathfrak{S}_t)$ is generated by these objects. We can define the functor

$$\text{Rep}(\mathfrak{S}_t) \to k\mathfrak{S}_t\text{-}\text{mod}$$

$$[m] \mapsto M_{(t-m,1^m)}.$$

which is fully faithful and preserves tensor product. Hence we can regard that:

**Proposition 2.19.** Deligne’s category $\text{Rep}(\mathfrak{S}_t)$ is a tensor full subcategory of $k\mathfrak{S}_t\text{-}\text{mod}\text{-}\text{cat}$. 

It is well-known that when $k$ is a field of characteristic zero, the category $\text{Rep}(\mathfrak{S}_m)$ is semisimple. Since every its simple object is obtained as a direct summand of the regular representation $M_{(1^m)} \simeq k\mathfrak{S}_m$, we have a category equivalence $\text{Rep}(\mathfrak{S}_t) \simeq k\mathfrak{S}_t\text{-}\text{mod}$. In contrast, if $k$ has a positive characteristic then the image of the embedding $\text{Rep}(\mathfrak{S}_t) \hookrightarrow k\mathfrak{S}_t\text{-}\text{mod}$ is a proper full subcategory. We remark that for each natural number $d \in \mathbb{N}$, Deligne’s category $\text{Rep}(\mathfrak{S}_d)$ only depends on
the scalar value $d \in k$ while our $k\mathfrak{S}_d\text{-Mod}$ gives different categories for each $d \in \mathbb{N}$. So $k\mathfrak{S}_d\text{-Mod}$ is considered to be capturing more precise structures in the modular case.

References


