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<td>Satoh, Takao</td>
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Kyoto University
SOME REMARKS ON THE JOHNSON HOMOMORPHISM OF THE AUTOMORPHISM GROUP OF A FREE GROUP

佐藤隆夫 (Takao Satoh)
東京大学大学院数理科学研究科 (The University of Tokyo)

Dedicated to Professor Yasuhiko Kitada on the occasion of his sixtieth birthday

ABSTRACT. In this paper we construct new obstructions for the surjectivity of the Johnson homomorphism of the automorphism group of a free group. We also determine the structure of the cokernel of the Johnson homomorphism for degrees 2 and 3.

1. Introduction

Let $F_n$ be a free group of rank $n \geq 2$ and $F_n = \Gamma_n(1), \Gamma_n(2), \ldots$ its lower central series. We denote by $\text{Aut} F_n$ the group of automorphisms of $F_n$. For each $k \geq 0$, let $A_n(k)$ be the group of automorphisms of $F_n$ which induce the identity on the quotient group $F_n/\Gamma_n(k+1)$. Then we have a descending filtration

$$\text{Aut} F_n = A_n(0) \supset A_n(1) \supset A_n(2) \supset \cdots$$

of $\text{Aut} F_n$. This filtration was introduced in 1963 with a remarkable pioneer work by S. Andreadakis [1] who showed that $A_n(1), A_n(2), \ldots$ is a descending central series of $A_n(1)$ and each graded quotient $\text{gr}^k(A_n) = A_n(k)/A_n(k+1)$ is a free abelian group of finite rank. He [1] also computed that $\text{rank}_\mathbb{Z} \text{gr}^k(A_2)$ for all $k \geq 1$ and $\text{rank}_\mathbb{Z} \text{gr}^2(A_3)$, and asserted $\text{rank}_\mathbb{Z} \text{gr}^3(A_3) = 44$. In Section 5, however, we show that $\text{gr}^3(A_3) = 43$. Moreover, by a recent remarkable work by A. Pettet [15] we have $\text{rank}_\mathbb{Z} \text{gr}^2(A_n) = \frac{1}{3}n^2(n^2 - 4) + \frac{1}{2}n(n - 1)$ for all $n \geq 3$. However, it is difficult to compute the rank of $\text{gr}^k(A_n)$.

Let $H$ be the abelianization of $F_n$ and $H^* = \text{Hom}_\mathbb{Z}(H, \mathbb{Z})$ the dual group of $H$. Let $\mathcal{L}_n = \bigoplus_{k \geq 1} \mathcal{L}_n(k)$ be the free graded Lie algebra generated by $H$. Then for each $k \geq 1$, a $GL(n, \mathbb{Z})$-equivariant injective
homomorphism
\[ \tau_k : \text{gr}^k(\mathcal{A}_n) \to H^* \otimes \mathcal{L}_n(k + 1) \]
is defined. (For definition, see Section 2.) This is called the \( k \)-th Johnson homomorphism of \( \text{Aut} F_n \). The theory of the Johnson homomorphism of a mapping class group of a compact Riemann surface began in 1980 by D. Johnson [6] and has been developed by many authors. There is a broad range of remarkable results for the Johnson homomorphism of a mapping class group. (For example, see [5] and [13].) However, the properties of the Johnson homomorphism of \( \text{Aut} F_n \) are far from being well understood.

The main interest of this paper is to determine the structure of the cokernel of the Johnson homomorphism \( \tau_k \) as a \( GL(n, \mathbb{Z}) \)-module. For \( k = 1 \), it is a well known fact that the first Johnson homomorphism \( \tau_1 \) is an isomorphism. (See [8].) For \( k \geq 2 \), the Johnson homomorphism \( \tau_k \) is not surjective. In fact, a recent remarkable work by Shigeyuki Morita indicates that there is a symmetric product \( S^k H_Q \) of \( H_Q = H \otimes \mathbb{Q} \) in the cokernel of \( \tau_{k,Q} = \tau_k \otimes \text{id}_Q \) for each \( k \geq 2 \). To show this, he introduced a homomorphism
\[ \text{Tr}_k : H^* \otimes \mathcal{L}_n(k + 1) \to S^k H, \]
called the trace map, and showed that \( \text{Tr}_k \) vanishes on the image of \( \tau_k \) and is surjective after tensoring with \( \mathbb{Q} \) for all \( k \geq 2 \).

The trace maps were introduced in the 1993 by Morita [12] for a Johnson homomorphism of a mapping class group of a surface. He called these maps traces because they were defined using the trace of some matrix representation. Morita's traces are very important to study the Lie algebra structure of the target \( H^* \otimes \mathcal{L}_n = \text{Der}(\mathcal{L}_n) \) of the Johnson homomorphisms. Here \( \text{Der}(\mathcal{L}_n) \) denotes the graded Lie algebra of derivations of \( \mathcal{L}_n \). Morita conjectured that for any \( n \geq 3 \), the abelianization of the Lie algebra \( \text{Der}(\mathcal{L}_n) \) is given by
\[ H_1(\text{Der}(\mathcal{L}_n^Q)) \simeq (H_Q^* \otimes \Lambda^2 H_Q) \oplus \bigoplus_{k \geq 2} S^k H_Q \]
where \( \mathcal{L}_n^Q = \mathcal{L}_n \otimes \mathbb{Q} \) and the right hand side is understood to be an abelian Lie algebra. Recently, combining a work of Kassabov [7] with the concept of the traces, he [14] showed that the isomorphism above holds up to degree \( n(n - 1) \).
The subgroup $\mathcal{A}_n(1)$ is called the IA-automorphism group of $F_n$ and denoted by $IA_n$. The group $IA_n$ is the kernel of the natural map $\text{Aut} F_n \to GL(n, \mathbb{Z})$ which is given by the action of $\text{Aut} F_n$ on $H$. The structures of $IA_n$ plays an important role in the study $\text{Aut} F_n$. W. Magnus [10] showed that $IA_n$ is finitely generated for all $n \geq 3$. However, it is not known whether $IA_n$ is finitely presented or not for any $n \geq 4$. For $n = 3$, by a remarkable work by S. Krstić and J. McCool [9], it is known that $IA_3$ is not finitely presented. On the other hand, the abelianization of $IA_n$ is given by

$$IA_n^{ab} \simeq H^* \otimes_{\mathbb{Z}} \Lambda^2 H$$

as a $GL(n, \mathbb{Z})$-module. (See [8].)

Now let $\mathcal{A}_n'(1)$, $\mathcal{A}_n'(2)$, $\ldots$ be the lower central series of $IA_n = \mathcal{A}_n(1)$ and $\text{gr}^k(\mathcal{A}_n')$ its graded quotient of it for each $k \geq 1$. In Section 2, we define a $GL(n, \mathbb{Z})$-equivariant homomorphism

$$\tau'_k : \text{gr}^k(\mathcal{A}_n') \to H^* \otimes \mathcal{L}_n(k + 1)$$

which is also called the $k$-th Johnson homomorphism of $\text{Aut} F_n$. In this paper, we construct new obstructions of the surjectivity of the Johnson homomorphism $\tau'_k$. Let us denote the tensor products with $\mathbb{Q}$ of a $\mathbb{Z}$-module by attaching a subscript $\mathbb{Q}$ to the original one. For example, $H_\mathbb{Q} := H \otimes_{\mathbb{Z}} \mathbb{Q}$ and $\mathcal{L}_n^\mathbb{Q}(k) := \mathcal{L}_n(k) \otimes_{\mathbb{Z}} \mathbb{Q}$. Similarly, for a $\mathbb{Z}$-linear map $f : A \to B$ we denote by $f_\mathbb{Q}$ the $\mathbb{Q}$-linear map $A_\mathbb{Q} \to B_\mathbb{Q}$ induced by $f$.

It is conjectured that $\text{Coker } \tau'_k,\mathbb{Q} = \text{Coker } \tau_k,\mathbb{Q}$ for $k \geq 1$. It is true for $1 \leq k \leq 3$. In fact, $\mathcal{A}_n(1) = \mathcal{A}_n'(1)$ by definition. We have $\mathcal{A}_n(2) = \mathcal{A}_n'(2)$ from the result stated above. (See [8].) Moreover, Pettet [15] showed that $\mathcal{A}_n'(3)$ has a finite index in $\mathcal{A}_n(3)$. Hence, $\text{Coker } \tau'_k,\mathbb{Q} = \text{Coker } \tau_k,\mathbb{Q}$ for $1 \leq k \leq 3$. Our main result is

**Theorem 1.**

1. $\Lambda^k H_\mathbb{Q} \subset \text{Coker } \tau'_k,\mathbb{Q}$ for odd $k$ and $3 \leq k \leq n$.
2. $H^{[2,1^{k-2}]}_\mathbb{Q} \subset \text{Coker } \tau'_k,\mathbb{Q}$ for even $k$ and $4 \leq k \leq n - 1$.

Here $\Lambda^k H_\mathbb{Q}$ denotes the $k$-th exterior product of $H_\mathbb{Q}$, and $H^{[2,1^{k-2}]}_\mathbb{Q}$ denotes the Schur-Weyl module of $H_\mathbb{Q}$ corresponding to the partition $[2,1^{k-2}]$.

In order to prove this, in Section 3, we introduce homomorphisms defined by

$$\text{Tr}_{[1^k]} := f_{[1^k]} \circ \Phi_1^k : H^* \otimes_{\mathbb{Z}} \mathcal{L}_n(k + 1) \to \Lambda^k H,$$

$$\text{Tr}_{[2,1^{k-2}]} := (id_H \otimes f_{[1^{k-3}]} \circ \Phi_2^k : H^* \otimes_{\mathbb{Z}} \mathcal{L}_n(k + 1) \to H \otimes_{\mathbb{Z}} \Lambda^{k-1} H$$
and show that these maps vanish on the image of the Johnson homomorphism \( \tau'_k \). Since these maps are constructed in a way similar to that of Morita’s trace \( \text{Tr}_k \), we also call these maps traces.

In Section 5, we determine the \( GL(n, \mathbb{Z}) \)-module structure of the cokernel of the Johnson homomorphism \( \tau_k \) for 2 and 3. Our result is

**Theorem 2.** We have \( GL(n, \mathbb{Z}) \)-equivariant exact sequences

\[
0 \to \text{gr}^2(A_n) \xrightarrow{\tau_k'} H^* \otimes \mathbb{Z} \to S^2 H \to 0
\]

and

\[
0 \to \text{gr}^3(A_n) \xrightarrow{\tau_k} H^*_Q \otimes \mathbb{Z} \to S^3 H_Q \oplus \Lambda^3 H_Q \to 0
\]

for \( n \geq 3 \).

Thus we have

**Corollary 1.** For \( n \geq 3 \),

\[
\text{rank}_\mathbb{Z} \text{gr}^3(A_n) = \frac{1}{12} n(3n^4 - 7n^2 - 8).
\]
2. Preliminaries

In this section we review some basic facts. First, we note that the group Aut $F_n$ acts on $F_n$ on the right. For any $\sigma \in \text{Aut } F_n$ and $x \in F_n$, the action of $\sigma$ on $x$ is denoted by $x^\sigma$.

2.1. Commutators of higher weight.

In this paper, we often use basic facts of commutator calculus. The reader is referred to [11] and [16], for example. Let $G$ be a group. For any elements $x$ and $y$ of $G$, the element

$$xyx^{-1}y^{-1}$$

is called the commutator of $x$ and $y$, and denoted by $[x,y]$. In general, a commutator of higher weight is recursively defined as follows. First, a commutator of weight 1 is an element of $G$. For $k > 1$, a commutator of weight $k$ is an element of the type $C = [C_1, C_2]$ where $C_j$ is a commutator of weight $a_j$ ($j = 1, 2$) such that $a_1 + a_2 = k$. The weight of the commutator $C$ is denoted by $\text{wt}(C) = k$. The commutator which has elements $g_1, \ldots, g_t \in G$ in the bracket components is called the commutator among the components $g_1, \ldots, g_t$. For elements $g_1, \ldots, g_t \in G$, a commutator of weight $k$ among the components $g_1, \ldots, g_t$ of the type

$$[[\cdots [[g_{i_1}, g_{i_2}], g_{i_3}], \cdots], g_{i_k}], \quad i_j \in \{1, \ldots, t\}$$

with all of its brackets to the left of all the elements occurring is called a simple $k$-fold commutator and is denoted by

$$[g_{i_1}, g_{i_2}, \cdots, g_{i_k}].$$

For each $k \geq 1$, the subgroups $\Gamma_G(k)$ of the lower central series of $G$ are defined recursively by

$$\Gamma_G(1) = G, \quad \Gamma_G(k + 1) = [\Gamma_G(k), G].$$

We use the following basic lemma in later sections.

Lemma 2.1. If a group $G$ is generated by $g_1, \ldots, g_t$, then each of the graded quotients $\Gamma_G(k)/\Gamma_G(k+1)$ for $k \geq 1$ is generated by the cosets of the simple $k$-fold commutators

$$[g_{i_1}, g_{i_2}, \cdots, g_{i_k}], \quad i_j \in \{1, \ldots, t\}.$$
associated graded sum. Then the set \( \text{gr}(\Gamma_n) \) naturally has a structure of a graded Lie algebra over \( \mathbb{Z} \) induced from the commutator bracket on \( F_n \). Let \( H \) be the abelianization of \( F_n \) and \( \mathcal{L}_n = \bigoplus_{k \geq 1} \mathcal{L}_n(k) \) the free graded Lie algebra generated by \( H \). It is well known that the Lie algebra \( \text{gr}(\Gamma_n) \) is isomorphic to \( \mathcal{L}_n \) as a graded Lie algebra over \( \mathbb{Z} \). Thus, in this paper, we identify \( \text{gr}(\Gamma_n) \) with \( \mathcal{L}_n \). For any element \( x \in \Gamma_n(k) \), we also denote by \( x \) the coset class of \( x \) in \( \mathcal{L}_n(k) = \Gamma_n(k)/\Gamma_n(k+1) \). Let \( T(H) \) be the tensor algebra of \( H \) over \( \mathbb{Z} \). Then the algebra \( T(H) \) is the universal enveloping algebra of the free Lie algebra \( \mathcal{L}_n \) and the natural map \( \mathcal{L}_n \to T(H) \) defined by

\[
[X, Y] \mapsto X \otimes Y - Y \otimes X
\]

for \( X, Y \in \mathcal{L}_n \) is an injective Lie algebra homomorphism. Hence we also regard \( \mathcal{L}_n(k) \) as a submodule of \( H^{\otimes k} \) for each \( k \geq 1 \).

### 2.2. IA-automorphism group.

The kernel of the natural map \( \text{Aut} F_n \to \text{GL}(n, \mathbb{Z}) \) which is given by the action of \( \text{Aut} F_n \) on \( H \) is called the IA-automorphism group of \( F_n \) and denoted by \( IA_n \). Let \( \{x_1, \ldots, x_n\} \) be a basis of a free group \( F_n \). Magnus [10] showed that \( IA_n \) is finitely generated by automorphisms

\[
K_{ab} : \begin{cases} 
  x_a &\mapsto x_b^{-1}x_a x_b, \\
  x_t &\mapsto x_t, \quad (t \neq a) 
\end{cases}
\]

and

\[
K_{abc} : \begin{cases} 
  x_a &\mapsto x_a x_b x_c x_b^{-1} x_c^{-1}, \\
  x_t &\mapsto x_t, \quad (t \neq a) 
\end{cases}
\]

for any distinct \( a, b \) and \( c \in \{1, 2, \ldots, n\} \). It is known that the abelianization \( IA_n^{ab} \) of the IA-automorphism group is free abelian group with generators \( K_{ab} \) for distinct \( a \) and \( b \), and \( K_{abc} \) for distinct \( a, b, c \) and \( b < c \). More precisely, if we denote by \( H^* = \text{Hom}_{\mathbb{Z}}(H, \mathbb{Z}) \) the dual group of \( H \), we have a \( \text{GL}(n, \mathbb{Z}) \)-module isomorphism \( IA_n^{ab} \simeq H^* \otimes_{\mathbb{Z}} \Lambda^2 H \). (For details, see [8].)

### 2.3. The associated graded Lie algebra.

Here we consider two descending filtrations of \( IA_n \). The first one is \( \{A_n(k)\}_{k \geq 1} \) defined as above. Since the series \( A_n(1), A_n(2), \ldots \) is central, the associated graded sum \( \text{gr}(A_n) = \bigoplus_{k \geq 1} \text{gr}^k(A_n) \) naturally has a structure of a graded Lie algebra over \( \mathbb{Z} \) induced from the commutator bracket on \( A_n(1) \). For each \( k \geq 1 \), the group \( A_n(0) = \text{Aut} F_n \) naturally acts on
\( \mathcal{A}_n(k) \) by conjugation, hence on \( \text{gr}^k(\mathcal{A}_n) \). Since the group \( \mathcal{A}_n(1) = IA_n \) trivially acts on \( \text{gr}^k(\mathcal{A}_n) \), we see that the group \( GL(n, \mathbb{Z}) \simeq \mathcal{A}_n(0)/\mathcal{A}_n(1) \) naturally acts on \( \text{gr}^k(\mathcal{A}_n) \).

The other is the lower central series \( \mathcal{A}'_n(1), \mathcal{A}'_n(2), \ldots \) of \( \mathcal{A}_n(1) \). Let \( \text{gr}^k(\mathcal{A}'_n) = \mathcal{A}'_n(k)/\mathcal{A}'_n(k+1) \) be the graded quotient for each \( k \geq 1 \). Similarly the associated graded sum \( \text{gr}(\mathcal{A}'_n) = \bigoplus_{k \geq 1} \text{gr}^k(\mathcal{A}'_n) \) has a structure of a graded Lie algebra structure on \( \mathbb{Z} \). Moreover, each graded quotient \( \text{gr}^k(\mathcal{A}'_n) \) is a \( GL(n, \mathbb{Z}) \)-module. It is clear that \( \mathcal{A}'_n(k) \subset \mathcal{A}_n(k) \) for every \( k \geq 1 \). In particular, we have \( \mathcal{A}'_n(k) = \mathcal{A}_n(k) \) for \( 1 \leq k \leq 2 \) and Pettet [15] showed that \( \mathcal{A}'_n(3) \) has finite index in \( \mathcal{A}_n(3) \) as mentioned in section 1. From Lemma 2.1, for each \( k \geq 1 \), the graded quotient \( \text{gr}^k(\mathcal{A}'_n) \) is generated by (the cosets of) the simple \( k \)-fold commutators among the components \( K_{ab} \) and \( K_{abc} \).

### 2.4. Johnson homomorphism.

Here we define the Johnson homomorphisms of \( \text{Aut} F_n \). For each \( k \geq 1 \), let \( \tau_k : \mathcal{A}_n(k) \to \text{Hom}_{\mathbb{Z}}(H, \mathcal{L}_n(k+1)) \) be the map defined by

\[
\sigma \mapsto (x \mapsto x^{-1}x^\sigma)
\]

for \( \sigma \in \mathcal{A}_n(k) \) and \( x \in H \). Then the map \( \tau_k \) is a homomorphism and the kernel of \( \tau_k \) is just \( \mathcal{A}_n(k+1) \). Hence, identifying \( \text{Hom}_{\mathbb{Z}}(H, \mathcal{L}_n(k+1)) \) with \( H^* \otimes_{\mathbb{Z}} \mathcal{L}_n(k+1) \), we obtain an injective \( GL(n, \mathbb{Z}) \)-equivariant homomorphism, also denoted by \( \tau_k \),

\[
\tau_k : \text{gr}^k(\mathcal{A}_n) \to H^* \otimes_{\mathbb{Z}} \mathcal{L}_n(k+1).
\]

This homomorphism is called the \( k \)-th Johnson homomorphism of \( \text{Aut} F_n \). Similarly, for each \( k \geq 1 \), we can define a homomorphism \( \tau'_k : \mathcal{A}'_n(k) \to \text{Hom}_{\mathbb{Z}}(H, \mathcal{L}_n(k+1)) \) as (1). Since \( \mathcal{A}'_n(k+1) \) is contained in the kernel of \( \tau'_k \), we obtain a \( GL(n, \mathbb{Z}) \)-equivariant homomorphism, also denoted by \( \tau'_k \),

\[
\tau'_k : \text{gr}^k(\mathcal{A}'_n) \to H^* \otimes_{\mathbb{Z}} \mathcal{L}_n(k+1).
\]

We also call the map \( \tau'_k \) the Johnson homomorphism of \( \text{Aut} F_n \).

Let \( \{x_1, \ldots, x_n\} \) be a basis of \( F_n \). It defines a basis of \( H \) as a free abelian group, also denoted by \( \{x_1, \ldots, x_n\} \). Let \( \{x_1^*, \ldots, x_n^*\} \) be the dual basis of \( H^* \). For any \( \sigma \in \mathcal{A}'_n(k) \), if we set \( s_i(\sigma) := x_i^{-1}x_i^\sigma \in \mathcal{L}_n(k+1) \) \( (1 \leq i \leq n) \) then we have

\[
\tau_k(\sigma) = \tau'_k(\sigma) = \sum_{i=1}^{n} x_i^* \otimes s_i(\sigma) \in H^* \otimes_{\mathbb{Z}} \mathcal{L}_n(k+1).
\]
Let $\text{Der} (\mathcal{L}_n)$ be the graded Lie algebra of derivations of $\mathcal{L}_n$. The degree $k$ part of $\text{Der} (\mathcal{L}_n)$ is expressed as $\text{Der} (\mathcal{L}_n)(k) = H^* \otimes_{\mathbb{Z}} \mathcal{L}_n(k)$. Thus we sometimes identify $\text{Der} (\mathcal{L}_n)$ with $H^* \otimes_{\mathbb{Z}} \mathcal{L}_n$. Then the Johnson homomorphism $\tau = \bigoplus_{k \geq 1} \tau_k$ is a graded Lie algebra homomorphism. In fact, if we denote by $\partial \sigma$ the element of $\text{Der} (\mathcal{L}_n)$ corresponding to an element $\sigma \in H^* \otimes_{\mathbb{Z}} \mathcal{L}_n$ and write the action of $\partial \sigma$ on $X \in \mathcal{L}_n$ as $X^{\partial \sigma}$ then we have

$$\tau_{k+l}^{/} ([\sigma, \tau]) = \sum_{i=1}^{n} x_i^* \otimes (s_i(\sigma)^{\partial \tau} - s_i(\tau)^{\partial \sigma}).$$

for any $\sigma \in A_n'(k)$ and $\tau \in A_n'(l)$.

In general, each $s_i(\sigma) \in \mathcal{L}_n(k+1)$ cannot be uniquely written as a sum of commutators among the components $x_1, \ldots, x_n$. In this paper, each $s_i(\sigma)$ is recursively computed in the following way. First, for $\sigma = K_{abc}$, we can set

$$s_a(K_{abc}) = [x_b, x_c], \quad s_t(K_{abc}) = 0 \text{ if } t \neq a.$$ 

For $\sigma = K_{ab}$, we see that

$$x_t^{-1} x_t^\sigma = \begin{cases} [x_a^{-1}, x_b^{-1}] & \text{if } t = a, \\ 1 & \text{if } t \neq a \end{cases}$$

in $F_n$. Since $[x_a^{-1}, x_b^{-1}] = [x_a, x_b]$ in $\mathcal{L}_n(2)$, so we can set

$$s_a(K_{ab}) = [x_a, x_b], \quad s_t(K_{ab}) = 0 \text{ if } t \neq a.$$ 

Next, if $\sigma = [\tau, K_{abc}]$ for $k$-fold simple commutator $\tau$, following from (2), we can set

$$s_i(\sigma) = s_i(\tau)^{\partial K_{abc}} - s_i(K_{abc})^{\partial \tau}$$

for each $i$. Furthermore, since a commutator bracket of weight $l$ is considered as a $l$-fold multilinear map from the cartesian product of $l$ copies of $\mathcal{L}_n(1)$ to $\mathcal{L}_n(l)$, we can also set

$$s_i(\sigma) = \sum_{p=1}^{a(i)} (-1)^{e_{i,p}} C_{i,p}$$

where $e_{i,p} = 0$ or $1$, and $C_{i,p}$ is a commutator of degree $k + 1$ among the components $x_1, \ldots, x_n$. We compute $s_i([\tau, K_{abc}])$ for $\sigma = [\tau, K_{abc}]$ similarly. These computations are perhaps easiest explained with examples, so we give two here. For distinct $a, b, c$ and $d$, we have
\[
\tau_{2}'([K_{ab}, K_{bac}]) = x_a^* \otimes ([x_a, x_b])^{\partial K_{bac}} - x_b^* \otimes ([x_a, x_c])^{\partial K_{ab}},
\]
\[
= x_a^* \otimes [x_a, [x_a, x_c]] - x_b^* \otimes [[x_a, x_b], x_c]
\]
and
\[
\tau_{3}'([K_{ab}, K_{bac}, K_{ad}]) = x_a^* \otimes ([x_a, [x_a, x_c]])^{\partial K_{ad}} - x_b^* \otimes ([x_a, x_d], x_c) - x_a^* \otimes ([x_a, x_d], x_c)
\]
\[
- x_a^* \otimes ([x_a, x_d], x_c]
\]

3. The contractions

For \( k \geq 1 \) and \( 1 \leq l \leq k + 1 \), let \( \varphi_{l}^{k} : H^* \otimes_{\mathbb{Z}} H^{\otimes(k+1)} \rightarrow H^{\otimes k} \) be the contraction map defined by

\[
x_{i}^* \otimes x_{j_{1}} \otimes \cdots \otimes x_{j_{k+1}} \mapsto x_{i}^* (x_{j_{1}} \otimes \cdots \otimes x_{j_{k+1}})
\]

For the natural embedding \( \iota_{n}^{k+1} : \mathcal{L}_{n}(k+1) \rightarrow H^{\otimes(k+1)} \), we obtain a \( GL(n, \mathbb{Z}) \)-equivariant homomorphism

\[
\Phi_{l}^{k} = \varphi_{l}^{k} \circ (id_{H^*} \otimes \iota_{n}^{k+1}) : H^* \otimes_{\mathbb{Z}} \mathcal{L}_{n}(k+1) \rightarrow H^{\otimes k}.
\]

We also call the map \( \Phi_{l}^{k} \) contraction.

Here we introduce one of methods of the computation of \( \Phi_{l}^{k}(x_{i}^* \otimes C) \) for a commutator \( C \in \mathcal{L}_{n}(k+1) \) among the components \( x_1, \ldots, x_n \). In this paper, whenever we compute \( \Phi_{l}^{k}(x_{i}^* \otimes C) \), we use the following method. First, if \( x_i \) does not appear among the components of \( C \), then \( \Phi_{l}^{k}(x_{i}^* \otimes C) = 0 \). On the other hand, if \( x_i \) appears among the components of \( C \) \( m \) times, then we distinguish them and write such \( x_i \)'s as \( x_{i_{1}}, \ldots, x_{i_{m}} \) in \( C \). Then \( \Phi_{l}^{k}(x_{i}^* \otimes C) \) is given by rewriting \( x_{i_{1}}, \ldots, x_{i_{m}} \) as \( x_{i} \) in

\[
\sum_{j=1}^{m} \Phi_{l}^{k}(x_{i_{j}}^* \otimes C).
\]

Thus it suffices to compute \( \Phi_{l}^{k}(x_{i}^* \otimes C) \) for a commutator \( C \) which has only one \( x_i \) in its components. Now, \( C \) is written as \([X, Y]\) for some commutators \( X \) and \( Y \). Rewriting the commutator \( C \) as \(-[Y, X]\) if \( x_i \) appears in \( Y \), we may always consider \( C = \pm[X, Y] \) such that \( x_i \) appears among the components of \( X \). By a recursive argument, we have \( C = \)
\[ \pm [x_i, C_1, \ldots, C_t] \text{ where each } C_j (1 \leq j \leq t) \text{ is a commutator of weight } d_j \text{ and } d_1 + \cdots + d_t = k. \]

**Lemma 3.1.** For a commutator \( [x_i, C_1, \ldots, C_t] \in \mathcal{L}_n(k+1) \) as above,
\[
\Phi^k_1(x_i^* \otimes [x_i, C_1, \ldots, C_t]) = C_1 \otimes \cdots \otimes C_t.
\]

**Lemma 3.2.** For a commutator \( [x_i, C_1, \ldots, C_t] \in \mathcal{L}_n(k+1) \) as above,
\[
\Phi^k_2(x_i^* \otimes [x_i, C_1, \ldots, C_t]) = - \sum_{\text{wt}(C_j) = 1} C_j \otimes C_1 \otimes \cdots \otimes C_{j-1} \otimes C_{j+1} \otimes \cdots \otimes C_t.
\]

Let \( T(H) = \bigoplus_{k \geq 1} H^\otimes k \) and \( S(H) = \bigoplus_{k \geq 1} S^k H \) be the tensor algebra and the symmetric algebra on \( H \) respectively. Then the kernel of a natural map \( T(H) \to S(H) \) is a graded ideal of \( T(H) \), and denoted by \( I(H) = \bigoplus_{k>1} I^k(H) \). For each \( k \geq 2 \), let \( \mathcal{U}_n(k) \) be the \( \text{GL}(n, \mathbb{Z})- \) submodule of \( H^\otimes k \) generated by elements type of
\[ [A, B] := A \otimes B - B \otimes A \]
for \( A \in H^\otimes a, B \in H^\otimes b \) and \( a + b = k \). If we put \( \mathcal{U}_n = \bigoplus_{k \geq 1} \mathcal{U}_n(k) \), then \( \mathcal{U}_n \) is the kernel of the abelianization \( T(H) \to T(H)^{ab} \) as a Lie algebra. We have
\[ \mathcal{L}_n(k) \subset \mathcal{U}_n(k) \subset I^k(H) \subset H^\otimes k. \]

**3.1. The image of \( \Phi^k_1 \circ \tau'_k \).**

Here we prove

**Proposition 3.1.** For \( n \geq 3 \) and \( k \geq 2 \), \( \text{Im}(\Phi^k_1 \circ \tau'_k) \subset \mathcal{U}_n(k) \).

It suffices to check that the image of any simple \( k \)-fold commutator \( \sigma \) among the components \( K_{ab} \) and \( K_{abc} \) is in \( \mathcal{U}_n(k) \). We have
\[
\tau'_k(\sigma) = \sum_{i=1}^n x_i^* \otimes s_i(\sigma), \quad s_i(\sigma) = \sum_{p=1}^{a(i)} (-1)^{e_{i,p}} C_{i,p}.
\]

Now, for convenience, for every \( t \in \{1, \ldots, n\} \), if each \( C_{i,p} \) has \( x_t \) in its components \( \beta(i,p,t) \) times, we distinguish them and write such \( x_i \)'s as \( x_{t_1}, \ldots, x_{t_{\beta(i,p,t)}} \) in \( C_{i,p} \). We denote by \( \bar{C}_{i,p} \) the element \( C_{i,p} \) whose components are distinguished as above. If we denote by \( \Phi^k_1(x_i^* \otimes \bar{C}_{i,p}) \).
the element of $H^\otimes k$ which is given by rewriting $x_{t_{1}}, \ldots, x_{t_{\beta(i,p,t)}}$ as $x_{t}$ in $\Phi_{1}^{k}(x_{i_{q}}^{*} \otimes \bar{C}_{i,p})$ for all $t$, then we have

\begin{equation}
\Phi_{1}^{k} \circ \tau'_{k}(\sigma) = \sum_{i=1}^{n} \sum_{p=1}^{\alpha(i)} \sum_{q=1}^{\beta(i,p,i)} (-1)^{e_{i,p}} \Phi_{1}^{k}(x_{i_{q}}^{*} \otimes \bar{C}_{i,p})_{\#}.
\end{equation}

Then Proposition 3.1 follows from Lemma 3.3.

**Lemma 3.3.** Let $k$ be an integer greater than 1. According to the notation as above, for each $i$, $p$ and $q$, one of the following holds:

(i) $\Phi_{1}^{k}(x_{i_{q}}^{*} \otimes \bar{C}_{i,p})_{\#} = 0$,

(ii) $\Phi_{1}^{k}(x_{i_{q}}^{*} \otimes \bar{C}_{i,p})_{\#} = X$; a commutator of weight $k$ in $\mathcal{L}_{n}(k)$

or

(iii) There exist some $j$, $p'$ and $q'$ such that $(j, p', q') \neq (i, p, q)$,

\begin{align*}
(-1)^{e_{i,p}} \Phi_{1}^{k}(x_{i_{q}}^{*} \otimes \bar{C}_{i,p})_{\#} &= \pm A \otimes B, \\
(-1)^{e_{j,p'}} \Phi_{1}^{k}(x_{j_{q'}}^{*} \otimes \bar{C}_{j,p'})_{\#} &= \mp B \otimes A
\end{align*}

where $A \in H^{\otimes \mu}$, $B \in H^{\otimes \nu}$ and $\mu + \nu = k$.

3.2. **The image of $\Phi_{2}^{k} \circ \tau'_{k}$.**

Here we prove

**Proposition 3.2.** For $n \geq 3$ and $k \geq 3$, $\text{Im} (\Phi_{2}^{k} \circ \tau'_{k}) \subset H \otimes_{Z} \mathcal{U}_{n}(k-1)$.

For each $i$, $p$ and $q$ in (3), if $\bar{C}_{i,p}$ has $x_{i_{q}}$, rewriting $\bar{C}_{i,p}$ as $\pm [x_{i_{q}}, D_{i,p}^{1}, \ldots, D_{i,p}^{\gamma(i,p,q)}]$, we have,

\begin{equation}
\Phi_{2}^{k}(x_{i_{q}}^{*} \otimes \bar{C}_{i,p}) = \sum_{\text{wt}(D_{i,p}^{t})=1} \mp (D_{i,p}^{t} \otimes D_{i,p}^{1} \otimes \cdots \otimes D_{i,p}^{t-1} \otimes D_{i,p}^{t+1} \otimes \cdots \otimes D_{i,p}^{\gamma(i,p,q)})_{\#}.
\end{equation}

Set $T(\bar{C}_{i,p}) := \{ t | \text{wt}(D_{i,p}^{t}) = 1 \}$. If $\bar{C}_{i,p}$ does not have $x_{i_{q}}$ or $T(\bar{C}_{i,p}) = 0$ then $\Phi_{2}^{k}(x_{i_{q}}^{*} \otimes \bar{C}_{i,p})_{\#} = 0$. If $T(\bar{C}_{i,p}) = 1$ and $\gamma(i,p,q) = 2$, then

\begin{equation}
\Phi_{2}^{k}(x_{i_{q}}^{*} \otimes \bar{C}_{i,p})_{\#} = \pm x_{\sigma} \otimes Z \in H \otimes_{Z} \mathcal{L}_{n}(k-1)
\end{equation}

for some commutator $Z$ of weight $k - 1$. Then Proposition 3.2 follows from

**Lemma 3.4.** Let $k$ be an integer greater than 2. According to the notation above, for each $i$, $p$ and $q$, one of the following holds:
(i) Either \( \overline{C}_{i,p} \) does not have \( x_{i_{q}} \), or \( T(\overline{C}_{i,p}) = 0 \),

(ii) \( T(\overline{C}_{i,p}) = 1 \) and \( \gamma(i, p, q) = 2 \),

or

(iii) For each \( t \in T(\overline{C}_{i,p}) \), there exist some \( j, p', q' \) and \( t' \), \( (j, p', q', t') \neq (i, p, q, t) \), such that if we set

\[
X := \mp(-1)^{e_{i,p}}(D_{i,p}^{t} \otimes D_{i,p}^{1} \otimes \ldots \otimes D_{i,p}^{\gamma(i,p,q)})_{\#} \check{t},
\]

\[
Y := \mp(-1)^{e_{j,p'}}(D_{j,p'}^{t'} \otimes D_{j,p'}^{1} \otimes \ldots \otimes D_{j,p'}^{\gamma(j,p',q',q')})_{\#} \check{t}'
\]

then \( X + Y = 0 \) or

\[
X = \pm x_{s} \otimes A \otimes B, \quad Y = \mp x_{s} \otimes B \otimes A
\]

where \( A \in H^{\otimes \mu}, B \in H^{\otimes \nu} \) and \( \mu + \nu = k - 1 \).

4. The trace maps

In this section, using the contractions defined in Section 3, we define a homomorphisms called the trace map which vanishes on the image of the Johnson homomorphism. Here we use some basic facts of the representation theory of \( GL(n, \mathbb{Z}) \). The reader is referred to, for example, Fulton-Harris [4] and Fulton [3].

For any \( k \geq 1 \) and any partition \( \lambda \) of \( k \), we denote by \( H^{\lambda} \) the Schur-Weyl module of \( H \) corresponding to the partition \( \lambda \) of \( k \). Let \( f_{\lambda} : H^{\otimes k} \to H^{\lambda} \) be a natural homomorphism. In this paper, we mainly consider the case for \( \lambda = [k] \) or \([1^{k}] \). The modules \( H^{[k]} \) and \( H^{[1^{k}]} \) are the symmetric product \( S^{k}H \) and the exterior product \( \Lambda^{k}H \) respectively. Using the natural map \( \iota_{n}^{k} : \mathcal{L}_{n}(k) \to H^{\otimes k} \), we denote \( f_{[1^{k}]} \circ \iota_{n}^{k}(C) \) by \( \hat{C} \) for any \( C \in \mathcal{L}_{n}(k) \).

**Lemma 4.1.** For any commutator \( C \) of weight \( k \geq 3 \), \( \hat{C} = 0 \) in \( \Lambda^{k}H \)

**Lemma 4.2.** For \( 1 \leq k \leq n - 2 \) and any commutator \( C \) of weight \( k + 1 \) among the components \( x_{1}, \ldots, x_{n} \) except for \( x_{i} \), there exists an element \( \sigma \in A'_{n}(k) \) such that

\[
\tau_{k}'(\sigma) = x_{i}^{*} \otimes C \in H^{*} \otimes_{\mathbb{Z}} \mathcal{L}_{n}(k+1).
\]

4.1. Morita's trace (Trace map for \( S^{k}H \)).

Here we consider the map

\[
\text{Tr}_{[k]} = f_{[k]} \circ \Phi_{1}^{k} : H^{*} \otimes_{\mathbb{Z}} \mathcal{L}_{n}(k+1) \to S^{k}H.
\]
By definition, this map coincides with the Morita's trace $\text{Tr}_k$. For $n \geq 3$ and $k \geq 2$, Morita defined the trace map $\text{Tr}_k$ using the Magnus representation of $\text{Aut} F_n$ and showed that $\text{Tr}_k$ vanishes on the image of $\tau_k$. By a recent work, he showed that $\text{Tr}_k^Q$ is surjective. Hence we have

**Theorem 4.1.** (Morita) For $n \geq 3$ and $k \geq 2$,

$$S^k H_Q \subset \text{Coker} \tau_{k,Q}.$$

**Corollary 4.1.** For $n \geq 3$ and $k \geq 2$,

$$\text{rank}_\mathbb{Z}(\text{Coker} (\tau_k)) \geq \binom{n+k-1}{k}.$$

### 4.2. Trace map for $\Lambda^k H$.

Here we consider the map

$$\text{Tr}_{[1^k]} := f_{[1^k]} \circ \Phi^k_1 : H^* \otimes_{\mathbb{Z}} \mathcal{L}_n(k+1) \to \Lambda^k H.$$

**Theorem 4.2.**

1. For $3 \leq k \leq n$, $\text{Tr}_{[1^k]}$ is surjective,
2. $\text{Im}(\text{Tr}_{[1^k]} \circ \tau'_k) = 0$ if $k$ is odd and $3 \leq k \leq n$,
3. $\text{Im}(\text{Tr}_{[1^k]} \circ \tau'_k) = 2(\Lambda^k H) \subset \Lambda^k H$ if $k$ is even and $4 \leq k \leq n - 2$.

**Corollary 4.2.** For an odd $k$ and $3 \leq k \leq n$,

$$\Lambda^k H_Q \subset \text{Coker} \tau'_{k,Q}.$$

**Corollary 4.3.** For an odd $k$ and $3 \leq k \leq n$,

$$\text{rank}_\mathbb{Z}(\text{Coker} (\tau'_k)) \geq \binom{n}{k}.$$

### 4.3. Trace map for $H^{[2,1^{k-2}]}$.

Here we consider the map

$$\text{Tr}_{[2,1^{k-2}]} := (id_H \otimes f^h_{[1^{k-1}]}) \circ \Phi^k_2 : H^* \otimes_{\mathbb{Z}} \mathcal{L}_n(k+1) \to H \otimes_{\mathbb{Z}} \Lambda^{k-1} H.$$

Let $I$ be the $GL(n, \mathbb{Z})$-submodule of $H \otimes_{\mathbb{Z}} \Lambda^{k-1} H$ defined by

$$I = \langle x \otimes z_1 \land \cdots \land z_{k-2} \land y + y \otimes z_1 \land \cdots \land z_{k-2} \land x \mid x, y, z_t \in H \rangle.$$

**Theorem 4.3.** For an even $k$ and $4 \leq k \leq n - 1$,

1. $\text{Im}(\text{Tr}_{[2,1^{k-1}]}^Q) = I_Q$,
2. $\text{Im}(\text{Tr}_{[2,1^{k-1}]} \circ \tau'_k) = 0$. 


Now we have \( H_{Q} \otimes_{\mathbb{Z}} \Lambda^{k-1}H \simeq H_{Q}^{[2,1^{k-2}]} \oplus \Lambda^{k}H \) from the representation theory of \( GL(n, \mathbb{Z}) \). For even \( k \), since \( I_{Q} \) is contained in the kernel of a natural map \( H_{Q} \otimes_{\mathbb{Z}} \Lambda^{k-1}H_{Q} \rightarrow \Lambda^{k}H_{Q} \) defined by \( x \otimes y_{1} \land \cdots \land y_{k-1} \mapsto x \land y_{1} \land \cdots \land y_{k-1} \), we have \( I_{Q} \simeq H_{Q}^{[2,1^{k-2}]} \).

**Corollary 4.4.** For an even \( k \) and \( 4 \leq k \leq n - 1 \),

\[
H_{Q}^{[2,1^{k-2}]} \subset \text{Coker} \tau_{k,Q}.
\]

**Corollary 4.5.** For an even \( k \) and \( 4 \leq k \leq n - 1 \),

\[
\text{rank}_{\mathbb{Z}}(\text{Coker} (\tau_{k}')) \geq (k - 1) \binom{n + 1}{k}.
\]

5. The cokernel of the Johnson homomorphism \( \tau_{k} \) for \( k = 2 \) and 3

5.1. **The case \( k = 2 \).**

In this subsection we consider the case where \( n \geq 3 \). From Theorem 4.1 and \( \text{rank}_{\mathbb{Z}}(\text{Coker} (\tau_{2})) = \binom{n+1}{2} \) by Pettet [15], we have a \( GL(n, \mathbb{Z}) \)-equivariant exact sequence

\[
0 \rightarrow \text{gr}^{2}(A_{n}) \xrightarrow{\tau_{2,Q}} H_{Q}^{*} \otimes_{\mathbb{Z}} \mathcal{L}_{n}(3) \rightarrow S^{2}H_{Q} \rightarrow 0.
\]

In this subsection we show that the exact sequence above holds before tensoring with \( Q \). Here are some examples of commutators of degree 2 among the components \( K_{ab} \) and \( K_{abc} \) and their images by the Johnson homomorphism \( \tau_{2} \).

\[
\begin{align*}
(C1): \quad & [K_{ab}, K_{ac}], \quad x_{a}^{*} \otimes [x_{a}, x_{c}] - x_{a}^{*} \otimes [x_{a}, [x_{a}, x_{c}]], \\
(C2): \quad & [K_{ab}, K_{acd}], \quad x_{a}^{*} \otimes [x_{c}, x_{d}], \\
(C3): \quad & [K_{ab}, K_{abc}], \quad x_{a}^{*} \otimes [x_{b}, x_{c}], \\
(C4): \quad & [K_{ab}, K_{bac}], \quad x_{a}^{*} \otimes (x_{a}, [x_{a}, x_{c}] - x_{b}^{*} \otimes [x_{a}, x_{b}, x_{c}], \\
(C5): \quad & [K_{abc}, K_{bad}], \quad x_{a}^{*} \otimes [x_{a}, x_{d}, x_{c}] - x_{b}^{*} \otimes [x_{b}, x_{c}, x_{d}], \\
(C6): \quad & [K_{abc}, K_{bac}], \quad x_{a}^{*} \otimes [x_{a}, x_{c}], - x_{b}^{*} \otimes [x_{b}, x_{c}, x_{d}].
\end{align*}
\]

**Theorem 5.1.** For \( n \geq 3 \),

\[
0 \rightarrow \text{gr}^{2}(A_{n}) \xrightarrow{\tau_{2}} H^{*} \otimes_{\mathbb{Z}} \mathcal{L}_{n}(3) \rightarrow S^{2}H \rightarrow 0
\]

is a \( GL(n, \mathbb{Z}) \)-equivariant exact sequence.
5.2. The case $k = 3$.

Next we compute the cokernel of the Johnson homomorphism $\tau_{3,Q}$ for $n \geq 3$ using the fact that $\text{Coker}\ \tau_{3,Q} = \text{Coker}\ \tau'_{3,Q}$. We use commutators of weight 3 among the components $K_{ab}$ and $K_{abc}$:

(C1-1): $[[K_{ab}, K_{ac}], K_{bd}]$,  
(C1-2): $[[K_{ab}, K_{ac}], K_{bc}]$,  
(C1-3): $[[K_{ab}, K_{ac}], K_{bc}]$,  
(C3-1): $[[K_{ab}, K_{abc}], K_{cab}]$,  
(C3-2): $[[K_{ab}, K_{abc}], K_{ca}]$,  
(C3-3): $[[K_{ab}, K_{abc}], K_{bad}]$,  
(C4-1): $[[K_{ab}, K_{bac}], K_{ac}]$,  
(C4-2): $[[K_{ab}, K_{bac}], K_{ba}]$,  
(C4-3): $[[K_{ab}, K_{bac}], K_{ad}]$,  
(C4-4): $[[K_{ab}, K_{bac}], K_{abc}]$,  
(C4-5): $[[K_{ab}, K_{bac}], K_{abc}]$,  
(C4-6): $[[K_{ab}, K_{bac}], K_{abc}]$,  
(C4-7): $[[K_{ab}, K_{bac}], K_{abc}]$,  
(C4-8): $[[K_{ab}, K_{bac}], K_{abc}]$,  
(C4-9): $[[K_{ab}, K_{bac}], K_{abc}]$.

Here are a few examples of their images by $\tau_{3}$:

(C1-1)': $x_{a}^{*} \otimes [[x_{a}, x_{c}], [x_{b}, x_{d}]] - x_{a}^{*} \otimes [[x_{a}, [x_{b}, x_{d}]], x_{c}]$,  
(C3-1)': $x_{a}^{*} \otimes [[x_{b}, [x_{a}, x_{b}]], x_{b}] - x_{a}^{*} \otimes [[[x_{b}, x_{a}], x_{b}], x_{b}]$,  
(C4-1)': $x_{a}^{*} \otimes [[x_{c}, [x_{a}, x_{c}]], x_{a}] + x_{a}^{*} \otimes [[[x_{c}, x_{a}], [x_{a}, x_{c}]] + x_{b}^{*} \otimes [[[x_{b}, [x_{a}, x_{c}]], x_{c}] - x_{a}^{*} \otimes [[[x_{c}, x_{a}], x_{a}], x_{c}]$.

**Theorem 5.2.** For $n \geq 3$,

$$0 \rightarrow \text{gr}^{3}_{Q}(A_{n}) \xrightarrow{\tau_{3,Q}} H_{Q}^{*} \otimes_{Z} \mathcal{L}_{n}^{Q}(4) \rightarrow S^{3}H_{Q} \oplus \Lambda^{3}H_{Q} \rightarrow 0$$

is a $GL(n, Z)$-equivariant exact sequence.

**Corollary 5.1.** For $n \geq 3$,

$$\text{rank}_{Z} \text{gr}^{3}(A_{n}) = \frac{1}{12}n(3n^{4} - 7n^{2} - 8).$$

In particular, substituting $n = 3$ into (4), we have $\text{rank}_{Z} \text{gr}^{3}(A_{3}) = 43$.

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GRADUATE SCHOOL OF MATHEMATICAL SCIENCES, THE UNIVERSITY OF TOKYO, 3-8-1 KOMABA
MEGuro-KU TOKYO 153-0041, JAPAN
E-mail address: takao@ms.u-tokyo.ac.jp