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HOMOTOPY CLASSIFICATION OF GENERALIZED PHRASES IN TURAEV’S THEORY OF WORDS

FUKUNAGA TOMONORI

Abstract. In 2005 V. Turaev introduced the theory of topology of words and phrases. Turaev defined an equivalence relation on generalized words and phrases which is called homotopy. This is suggested by the Reidemeister moves in the knot theory. Then Turaev gave the homotopy classification of generalized words with less than or equal to five letters. In this paper we give the classification of generalized phrases up to homotopy with less than or equal to three letters. To do this we construct a new homotopy invariant for nanophrases over any $\alpha$.

Keywords: words, phrases, homotopy of words and phrases

Mathematics Subject Classification 2000: Primary 57M99; Secondary 68R15

1. Introduction.

In [8] and [9], V. Turaev introduced the theory of topology of words and phrases. Words are finite sequences of letters in a given alphabet, letters are elements of an alphabet and phrases are finite sequences of words. Turaev defined generalized words which is called ´etale words as follows: Let $\alpha$ be an alphabet endowed with an involution $\tau: \alpha \to \alpha$. Let $A$ be an alphabet endowed with a mapping $| \cdot |: A \to \alpha$ which is called a projection. We call this $A$ an $\alpha$-alphabet. Then we call a pair an $\alpha$-alphabet $A$ and a word on $A$ an ´etale word. If all letters in $A$ appear exactly twice, then we call this ´etale word a nannoword.

Turaev introduced an equivalence relation which is called homotopy on nanowords. This equivalence relation is suggested by the Reidemeister moves in the theory of knots. Homotopy of nanowords is generated by isomorphism, and three homotopy moves. The first homotopy move is deformation that changes $x\alpha Ay$ into $xy$. The second homotopy move is deformation that changes $xAbyBAz$ into $xyz$ when $|A|$ is equal to $\tau(|B|)$. The third homotopy move is deformation that changes $xAbyclzBclt$ into $xB AlyC AzC Bt$ when $|A|$ and $|B|$ are equal to $|C|$ (Turaev defined more generalized equivalence relation which is called $S$-homotopy. However, in this paper, we treat only homotopy). Turaev defined homotopy of ´etale words via desingularization of ´etale words. Moreover in [9] Turaev defined homotopy of nanophrase in a similar manner.

Theory of words and phrases is applied for studying curves on surfaces. In [3] C. F. Gauss studied planar curves via words. Turaev applied generalized words and phrases for curves and knot diagrams. Turaev showed special cases of the theory of topology of phrases corresponds to the theory of stable equivalent classes of ordered,
pointed, oriented multi-component curves on surfaces and knot diagrams. Note that
the theory stable equivalence classes of ordered, pointed, oriented multi-component
curves on surfaces (respectively knot diagrams) is equivalent to the theory of or-
dered open flat virtual links (respectively ordered open virtual links). In this paper,
ordered links means each components of links are numerated. See also [5], [6], [7]
and [11] for more details. In this meaning, the theory of topology of words and
phrases is combinational extension of the theory of virtual knots and links.

Now the purpose of this paper is classification of generalized phrases (in this paper
we call it étale phrases) up to homotopy. Turaev gave the homotopy classification of
étale words with less than or equal to five letters in [8]. We will extend this result.
More precisely, in this paper, we give the classification of étale phrases with less
than or equal to three letters. To do this we use some known invariants which was
introduced in [1], [2] and [4]. Moreover we construct a new homotopy invariant.

The rest of this paper is constructed as follows. In the next section we review the
theory of topology of nanowords, étale words, nanophrases and étale phrases. In
Section 3 we introduce homotopy invariants of nanophrases which was introduced
in [1], [2] and [4]. Then we will define a new homotopy invariant for nanophrases.
In Section 4 and Section 5 we give the classification of étale phrases with less than
or equal to three letters without the condition on length of phrases.

2. Étale Phrases and Nanophrases.

In this section we introduce Turaev’s theory of words and phrases (See [8], [9] and

2.1. Étale words and étale phrases. In this paper an alphabet means a finite set
and letters mean its element. A word of length $n$ on an alphabet $A$ is a mapping
$w : \hat{n} \rightarrow A$ where $\hat{n} := \{1, 2, \cdots, n\}$ and a phrase of length $k$ on $A$ is a finite sequence
of words on $A$, $(w_1 | w_2 | \cdots | w_k)$. A multiplicity of a letter $A \in A$ in a phrase $P$ on $A$ is a number of $A$ in the phrase $P$. We denote multiplicity of $A \in A$ by $m_P(A)$.

Let $\alpha$ be an alphabet endowed with an involution $\tau : \alpha \rightarrow \alpha$. An $\alpha$-alphabet is a
pair $(An alphabet A, mapping | \cdot | : A \rightarrow \alpha)$. We call the mapping $| \cdot |$ projection.

In [11], V. Turaev defined generalized words which is called étale words. An étale
word over $\alpha$ is a pair $(An \alpha\text{-alphabet } A, A$ word on $A)$ and A étale phrase over $\alpha$
is a pair $(An \alpha\text{-alphabet } A, A$ phrase on $A)$.

Remark 2.1. Turaev did not define étale phrases explicitly. However Turaev consid-
ered an equivalent object in [9].

A phrase $P$ on an $\alpha$ gives rise to an étale phrase $(\alpha, P)$ where the projection
$\alpha \rightarrow \alpha$ is the identity mapping. In this meaning étale phrases are generalization of
usual phrases.

2.2. Nanowords and nanophrases. A Gauss word on an alphabet $A$ is a word
$w$ on $A$ which all letters in $A$ appear exactly twice in $w$. A phrase $P$ on $A$ is called
a Gauss phrase if all letters in $A$ appear exactly twice in $P$.

In this paper, we consider generalized Gauss words and Gauss phrases. A nanoword
over $\alpha$ is a pair $(An \alpha\text{-alphabet } A, A$ Gauss word on $A)$ and A nanophrase over $\alpha$
is a pair (An α-alphabet \( \mathcal{A} \), a Gauss phrase on \( \mathcal{A} \)). Instead of writing \( (\mathcal{A}, P) \) for a nanophrase over \( \alpha \), we often write simply \( P \). The alphabet \( \mathcal{A} \) can be uniquely recovered. However the projection \( | \cdot | : \mathcal{A} \rightarrow \alpha \) should be always specified.

2.3. Desingularization of étale phrases. In this section, we introduce a method of associating with any étale phrases over \( \alpha (\mathcal{A}, P) \) a nanophrase over \( \alpha (\mathcal{A}^d, P^d) \) which is called desingularization of étale phrases.

Let \( \mathcal{A}^d \) be an \( \alpha \)-alphabet \( \{A_{ij} := (A, i, j) | A \in \mathcal{A}, 1 \leq i < j \leq m_P(A) \} \) with the projection \( |A_{ij}| := |A| \) for all \( A_{ij} \). The phrase \( P^d \) is obtained from \( P \) by first deleting all \( A \in \mathcal{A} \) with \( m_P(A) \) is greater than or equal to two and each \( i = 1, 2, \ldots m_P(A) \), we replace the \( i \)-th entry of \( A \) in \( P \) by

\[
A_{1,i}A_{2,i} \cdots A_{i-1,i}A_{i,i+1}A_{i,i+2} \cdots A_{i,m_P(A)}.
\]

The resulting \( (\mathcal{A}^d, P^d) \) is a nanophrase with \( \sum m_P(A)(m_P(A) - 1) \) letters and called a desingularization of \( (\mathcal{A}, P) \). Note that if \( (\mathcal{A}, P) \) is a nanophrase, then desingularization of \( (\mathcal{A}, P) \) is itself.

2.4. Homotopy of nanophrases and étale phrases. In [8] and [9], Turaev defined an equivalence relation which is called homotopy on a set of nanophrases and étale words.

To define homotopy, we define isomorphism of étale phrases. A morphism of \( \alpha \)-alphabets \( \mathcal{A}_1, \mathcal{A}_2 \) is a set-theoric mapping \( f : \mathcal{A}_1 \rightarrow \mathcal{A}_2 \) such that \( |A| = |f(A)| \) for all \( A \in \mathcal{A}_1 \). If \( f \) is bijective, then this morphism is an isomorphism. Two étale phrases \( (\mathcal{A}_1, (w_1| \cdots |w_k)) \) and \( (\mathcal{A}_2, (v_1| \cdots |v_k)) \) over \( \alpha \) are isomorphic if there is an isomorphism \( f : \mathcal{A}_1 \rightarrow \mathcal{A}_2 \) such that \( v_j = f \circ w_j \) for all \( j \in \hat{k} \).

Next we define homotopy moves of nanophrases.

Definition 2.1. We define homotopy moves (1) - (3) of nanophrases as follows:

1. \( (\mathcal{A}, (xA|Ay)) \rightarrow (\mathcal{A} \setminus \{A\}, (xy)) \)
   for all \( A \in \mathcal{A} \) and \( x, y \) are sequences of letters in \( \mathcal{A} \setminus \{A\} \), possibly including the \( | \cdot | \) character.

2. \( (\mathcal{A}, (xAb|BAy)) \rightarrow (\mathcal{A} \setminus \{A, B\}, (xyz)) \)
   if \( A, B \in \mathcal{A} \) satisfy \( |B| = \tau(|A|) \). \( x, y, z \) are sequences of letters in \( \mathcal{A} \setminus \{A, B\} \), possibly including \( | \cdot | \) character.

3. \( (\mathcal{A}, (xAbAyACzB)|t) \rightarrow (\mathcal{A}, (xB|AyCAzCB|t)) \)
   if \( A, B, C, \mathcal{A} \in \mathcal{A} \) satisfy \( |A| = |B| = |C| \). \( x, y, z, t \) are sequences of letters in \( \mathcal{A} \), possibly including \( | \cdot | \) character.

Now we define homotopy of étale phrases.

Definition 2.2. Two étale phrases \( (\mathcal{A}_1, P_1) \) and \( (\mathcal{A}_2, P_2) \) over \( \alpha \) are homotopic (denoted \( (\mathcal{A}_1, P_1) \simeq (\mathcal{A}_2, P_2) \)) if \( ((\mathcal{A}_2)^d, (P_2)^d) \) can be obtained from \( ((\mathcal{A}_1)^d, (P_1)^d) \) by a finite sequence of isomorphism, homotopy moves (1) - (3) and the inverse of moves (1) - (3).

Remark 2.2. By the definition of homotopy of étale phrases, every homotopy invariant \( I \) of nanophrases extends to a homotopy invariant \( I \) of étale phrases by \( I(P) := I(P^d) \).
The goal of this paper is to classify étale phrases of length $k$ over $\alpha$ with less than or equal to three letters up to homotopy for any $k$ and $\alpha$.

The case of $k$ is equal to one (in other words, the case of étale words) Turaev gave the classification as follows.

**Theorem 2.1** (Turaev [8]). A multiplicity-one-free word of length less than or equal to four in the alphabet $\alpha$ has one of the following forms: $aa, aaa, aaaa, aabb, abba, abab$ with distinct $a, b \in \alpha$. The words $aa, aabb, abba$ are contractible. The words $aaa$ and $aaaa$ are contractible if and only if $\tau(a) = a$. The word $abab$ is contractible if and only if $\tau(a) = b$. Non-contractible words of type $aaa, aaaa$ and $abab$ are homotopic if and only if they are equal.

### 3. Homotopy Invariants of Nanophrases.

By the definition of homotopy of étale phrases, we need homotopy invariants of nanophrases. In this section, we introduce homotopy invariants of nanophrases which were defined in [1], [2] and [4]. Moreover we define a new homotopy invariant of nanophrases.

#### 3.1. Simple invariants.

In this subsection, we review homotopy invariants which were defined in [2] and [4].

Let $P = (w_1|w_2|\cdots|w_k)$ be a nanophrase over $\alpha$. For $l \in \hat{k}$, we define $w(l) \in \mathbb{Z}/2\mathbb{Z}$ by the length of $w_l$. We call the vector

$$w(P) := (w(1), \cdots, w(k)) \in (\mathbb{Z}/2\mathbb{Z})^k$$

the component length vector.

**Proposition 3.1** (A. Gibson [4], see also [1]). The component length vector is a homotopy invariant of nanophrases.

Next we define another homotopy invariant. Let $\pi$ be the group which is defined as follows:

$$\pi := \langle a \in \alpha | a\tau(a) = 1, ab = ba \text{ for all } a, b \in \alpha \rangle.$$  

Let $(w_1|w_2|\cdots|w_k)$ be a nanophrase of length $k$ over $\alpha$. We define $l_P(i, j) \in \pi$ for $i < j$ by

$$l_P(i, j) := \prod_{A \in \text{Im}(w_i) \cap \text{Im}(w_j)} |A|.$$  

We call a vector $lk(P) := (l_P(1, 2), l_P(1, 3), \cdots, l_P(1, k), l_P(2, 3), \cdots, l_P(k - 1, k)) \in \pi^{\frac{1}{2}k(k-1)}$ the linking vector.

**Proposition 3.2** ([2]). The linking vector of nanophrases is a homotopy invariant of nanophrases.
3.2. The invariant $T$. In this section we introduce a homotopy invariant $T$ which was defined by the author in [1]. This invariant is defined for nanophrases over $\alpha_0$ and the one-element set where $\alpha_0 = \{a, b\}$ with the involution $\tau_0 : a \mapsto b$.

**Definition 3.1.** Let $P = (\mathcal{A}, (w_1 \cdots |w_k))$ be a nanophrase over $\alpha_0$ and $A, B \in \mathcal{A}$. Then we define $\sigma_P(A, B)$ as follows: If $A$ and $B$ form $\cdots A \cdots B \cdots$ in $P$ and $|B| = a$, or $\cdots B \cdots A \cdots B \cdots$ in $P$ and $|B| = b$, then $\sigma_P(A, B) := 1$. If $\cdots A \cdots B \cdots A \cdots B \cdots$ in $P$ and $|B| = a$, then $\sigma_P(A, B) := -1$. Otherwise $\sigma_P(A, B) := 0$.

**Definition 3.2.** For $A \in \mathcal{A}$ we define $\varepsilon(A) \in \{\pm 1\}$ by

$$\varepsilon(A) := \begin{cases} 1 & \text{if } |A| = a, \\ -1 & \text{if } |A| = b. \end{cases}$$

**Definition 3.3.** Let $P = (\mathcal{A}, (w_1|w_2| \cdots |w_k))$ be a nanophrase of length $k$ over $\alpha_0$. For $A \in \mathcal{A}$ such that there exist $i \in \{1, 2, \cdots, k\}$ such that $\text{Card}(w_i^{-1}(A)) = 2$, we define $T_P(A) \in \mathbb{Z}$ by

$$T_P(A) := \varepsilon(A) \sum_{B \in A} \sigma_P(A, B),$$

and we define $T_P(w_i) \in \mathbb{Z}$ by

$$T_P(w_i) := \sum_{A \in \mathcal{A}, \text{Card}(w_i^{-1}(A)) = 2} T_P(A).$$

Then we define $T(P) \in \mathbb{Z}^k$ by

$$T(P) := (T_P(w_1), T_P(w_2), \cdots, T_P(w_k)).$$

**Theorem 3.1 ([1]).** $T$ is a homotopy invariant of nanophrases over $\alpha_0$.

Next we define an invariant $T$ for nanophrases over the one-element set (we use the same notation “$T$” because of the Remark 3.1).

**Definition 3.4.** Let $P := (\mathcal{A}, (w_1|\cdots|w_k))$ be a nanophrase over the one-element set $\alpha := \{a\}$. Let $A, B \in \mathcal{A}$ be letters. Then we define $\tilde{\sigma}_P(A, B) \in \mathbb{Z}/2\mathbb{Z}$ as follows: If $A$ and $B$ form $\cdots A \cdots B \cdots A \cdots B \cdots$ or $\cdots B \cdots A \cdots B \cdots A \cdots$ in $P$, then $\tilde{\sigma}_P(A, B) := 1$. Otherwise $\tilde{\sigma}_P(A, B) := 0$.

**Definition 3.5.** Let $P := (\mathcal{A}, (w_1|\cdots|w_k))$ be a nanophrase over $\alpha := \{a\}$. For $A \in \mathcal{A}$ such that there exist an $i \in \{1, 2, \cdots, k\}$ such that $\text{Card}(w_i^{-1}(A)) = 2$, we define $T_P(A) \in \mathbb{Z}/2\mathbb{Z}$ by

$$T_P(A) := \sum_{B \in A} \tilde{\sigma}_P(A, B) \in \mathbb{Z}/2\mathbb{Z},$$

and $T_P(w_i) \in \mathbb{Z}/2\mathbb{Z}$ by

$$T_P(w_i) := \sum_{A \in \mathcal{A}, \text{Card}(w_i^{-1}(A)) = 2} T_P(A).$$

Then we define $T(P) \in (\mathbb{Z}/2\mathbb{Z})^k$ by

$$T(P) := (T_P(w_1), T_P(w_2), \cdots, T_P(w_k)).$$
Then the next theorem follows.

**Theorem 3.2** ([1]). \( T \) is a homotopy invariant of nanophrases over the one-element set.

**Remark 3.1.** In a preprint [2], the author extended the invariant \( T \) to nanophrases over any \( \alpha \). However in this paper we only use this invariant for nanophrases over \( \alpha_0 \) and nanophrases over the one element set.

3.3. The invariant \( S_\alpha \). In [4] A. Gibson defined a homotopy invariant of nanophrases over the one-element set which is stronger than the invariant \( T \) for nanophrases over the one-element set. In this subsection we introduce Gibson’s \( S_\alpha \) invariant.

First we define some notations. Let \( (A, P = (w_1, \ldots, w_k)) \) be a nanophrase over the one-element set. For a letter \( A \in A_i := \{A \in A : \text{Card}(w_i^{-1}(A)) = 2 \} \), we define \( f_j(A) \in \mathbb{Z}/2\mathbb{Z} \) as follows: If we write \( P \) as \( xA_yAz \) where \( x, y \) and \( z \) are words in \( A \) possibly including “\( \alpha \)” character, \( f_j(A) \) is the number of letters which appear exactly once in \( y \) and once in the \( j \)-th component of the phrase \( P \). Then we define \( l(A) \in (\mathbb{Z}/2\mathbb{Z})^k \) by

\[
l(A) := (l_1(A), l_2(A), \ldots, l_k(A)).
\]

Let \( v \) be a vector in \( (\mathbb{Z}/2\mathbb{Z})^k \). Then we define \( d_j(v) \in \mathbb{Z} \) by

\[
d_j(v) := \text{Card}(\{A \in A_i | l(A) = v\}),
\]

and we define \( B_j(P) \in 2^{(\mathbb{Z}/2\mathbb{Z})^k} \) by

\[
B_j(P) := \{v \in (\mathbb{Z}/2\mathbb{Z})^k \setminus \{0\} | d_j(v) = 1 \text{ mod } 2\}.
\]

Then we define the \( S_{\alpha_0}(P) \in (2^{(\mathbb{Z}/2\mathbb{Z})^k}) \) by

\[
S_{\alpha_0}(P) := (B_1(P), B_2(P), \ldots, B_k(P)).
\]

**Theorem 3.3** (Gibson [4]). \( S_{\alpha} \) is a homotopy invariant of nanophrases over the one-element set.

3.4. The invariant \( U_L \). In this section we introduce a new invariant of nanophrases.

First we prepare some notations. Since the set \( \alpha \) is a finite set, we obtain following orbit decomposition of the \( \tau : \alpha/\tau = \{\widehat{a}_{i_1}, \widehat{a}_{i_2}, \ldots, \widehat{a}_{i_l}, \widehat{a}_{i_{l+1}}, \ldots, \widehat{a}_{i_{l+m}}\} \), where \( \widehat{a}_{i_j} := \{a_{i_j}, \tau(a_{i_j})\} \) such that \( \text{Card}(\widehat{a}_{i_j}) = 2 \) for all \( j \in \{1, \ldots, l\} \) and \( \text{Card}(\widehat{a}_{i_j}) = 1 \) for all \( j \in \{l + 1, \ldots, l + m\} \) (we fix a complete representative system \( \text{crs}(\alpha/\tau) := \{a_{i_1}, a_{i_2}, \ldots, a_{i_l}, a_{i_{l+1}}, \ldots, a_{i_{l+m}}\} \) which satisfy the above condition). Let \( L \) be a subset of \( \text{crs}(\alpha/\tau) \). For a nanophrase \( (A, P) \) over \( \alpha \), we define a nanophrase \( U_L((A, P)) \) over \( L \cup \tau(L) \) as follows: deleting all letters \( A \in A \) such that \( |A| \notin L \cup \tau(L) \) from both \( A \) and \( P \).

**Proposition 3.3.** \( U_L \) is a homotopy invariant of nanophrases.

**Proof.** First, isomorphism does not change \( U_L(P) \) up to isomorphic is clear.

Consider the first homotopy move

\[
P_1 := (A, (xAY)) \to P_2 := (A \setminus \{A\}, (xy))
\]
where $x$ and $y$ are words on $\mathcal{A}$, possibly including ”|” character. Suppose $|A| \in L \cup \tau(L)$. Then
\[ U_L(P_1) = x_L \cdot A \cdot y_L y_L = U_L(P_2) \]
where $x_L$ and $y_L$ are words which obtained by deleting all letters $X \in \mathcal{A}$ such that $X \notin L \cup \tau(L)$ from $x$ and $y$ respectively.

Suppose $|A| \notin L \cup \tau(L)$. Then
\[ U_L(P_1) = x_L y_L y_L = U_L(P_2). \]
So the first homotopy move does not change the homotopy class of $U_L(P)$.

Consider the second homotopy move
\[ P_1 := (\mathcal{A}, (xAByBAz)) \longrightarrow P_2 := (\mathcal{A} \setminus \{A, B\}, (xyz)) \]
where $|A| = \tau(|B|)$, and $x, y$ and $z$ are words on $\mathcal{A}$ possibly including ”|” character. Suppose $|A| \in L \cup \tau(L)$. Then $|B| \in L \cup \tau(L)$ since $|A| = \tau(|B|)$. So
\[ U_L(P_1) = x_L A B y_L B A_2 z_2 \simeq x_L y_L z_2 = U_L(P_2). \]
Suppose $|A| \notin L \cup \tau(L)$. Then $|B| \notin L \cup \tau(L)$ since $|A| = \tau(|B|)$. So
\[ U_L(P_1) = x_L y_L z_2 = U_L(P_2). \]
By the above, the second homotopy move does not change the homotopy class of $U_L(P)$.

Consider the third homotopy move
\[ P_1 := (\mathcal{A}, (xAByACzBCt)) \longrightarrow P_2 := (\mathcal{A}, (xBAyCAzCBt)) \]
where $|A| = |B| = |C|$, and $x, y, z$ and $t$ are words on $\mathcal{A}$ possibly including ”|” character. Suppose $|A| \in L \cup \tau(L)$. Then $|B|, |C| \in L \cup \tau(L)$ since $|A| = |B| = |C|$. So we obtain
\[ U_L(P_1) = x_L A B y_L A C t_2 z_2 \simeq x_L B A y_L C A z_2 C B t_2 L = U_L(P_2). \]
Suppose $|A| \notin L \cup \tau(L)$. Then $|B|, |C| \notin L \cup \tau(L)$ since $|A| = |B| = |C|$. So we obtain
\[ U_L(P_1) = x_L y_L z_2 t_2 L = U_L(P_2). \]
So the third homotopy move does not change the homotopy class of $U_L(P)$.

By the above, $U_L$ is a homotopy invariant of nanophrases.

\[ \square \]

\section*{4. Homotopy Classification of Étale Phrases.}

In this section we classify étale phrases with less than or equal to three letters up to homotopy. First we recall lemmas in [1].

\begin{lemma}
Let $\beta$ be $\tau$-invariant subset of $\alpha$. If two nanophrases over $\beta$ are homotopic in the class of nanophrases over $\alpha$, then they are homotopic in the class of nanophrases over $\beta$.
\end{lemma}

\begin{lemma}
Let $P_1 = (w_1|w_2|\cdots|w_k)$ and $P_2 = (v_1|v_2|\cdots|v_k)$ be nanophrases of length $k$ over $\alpha$. If $P_1$ and $P_2$ are homotopic as nanophrases, then $w_i$ and $v_i$ are homotopic as étale words for all $i \in \{1, 2, \cdots, k\}$.
\end{lemma}
Next we prepare some notations. Let $\alpha$ be an alphabet endowed with an involution $\tau: \alpha \to \alpha$. Then we set
\[ P^{1;1,l_1,l_2} := (\emptyset \cdots | \alpha \cdots | \emptyset), \]
\[ P^{3;l} := (\emptyset \cdots | \alpha \cdots | \emptyset), \]
\[ P^{2,1;l_1,l_2} := (\emptyset \cdots | \alpha \cdots | \emptyset), \]
\[ P^{2,1,1;l_1,l_2} := (\emptyset \cdots | \alpha \cdots | \emptyset), \]
\[ P^{1,2;1,l_1,l_2} := (\emptyset \cdots | \alpha \cdots | \emptyset), \]
where $a \in \alpha$ and $l, l_1, l_2, l_3 \in k$ with $l_1 < l_2 < l_3$. Note that if $a = \tau(a)$, then $P^{3;l}_a$ is homotopic to the nanophrase $(\emptyset)_k := (\emptyset \cdots | \emptyset)$. So when we use the notation $P^{3;l}_a$, we always assume that $a \neq \tau(a)$.

Remark 4.1. For two different integers $k_1$ and $k_2$, an étale phrase of length $k_1$ and an étale phrase of length $k_2$ are not homotopic each other. So we do not write length of phrases in above notations.

Now we describe the main results of this paper.

**Theorem 4.1.** Let $P$ be a multiplicity-one-free étale phrase over $\alpha$ with less than or equal to three letters. Then $P$ is either homotopic to $(\emptyset)_k$ or homotopic to one of the following étale phrases: $P^{1;1,l_1,l_2}_a$, $P^{3;l}_a$, $P^{2,1;l_1,l_2}_a$, $P^{1,2;1,l_1,l_2}_a$, $P^{1,1,1;l_1,l_2,l_3}_a$ for some $l_1$, $l_2$, $l_3 \in k$ and $a \in \alpha$. Moreover $P^{1,1,1;l_1,l_2,l_3}_a$ are homotopic if and only if they are equal.

To prove this theorem, we prepare following lemmas.

**Lemma 4.3.** Étale phrases $P^{1;1,l_1,l_2}_a$, $P^{3;l}_a$, $P^{2,1;l_1,l_2}_a$, $P^{1,2;1,l_1,l_2}_a$, and $P^{1,1,1;l_1,l_2,l_3}_a$ are not homotopic to $(\emptyset)_k$.

**Lemma 4.4.** If $a$ is not equal to $b$, then $P^{X_1;Y_1}_a$ and $P^{X_2;Y_2}_b$ are not homotopic for all $(X_1;Y_1), (X_2;Y_2) \in \{ (1, 1; l_1, l_2), (3; l), (2, 1; l_1, l_2), (1, 2; l_1, l_2), (1, 1, 1; l_1, l_2, l_3) \}$.

**Lemma 4.5.** Two étale phrases $P^{X_1;Y_1}_a$ and $P^{X_2;Y_2}_a$ are homotopic if and only if $(X_1;Y_1)$ is equal to $(X_2;Y_2)$.

If we show above lemmas, then we obtain the main theorem. We prove these lemmas in the next section.

5. Proof of Lemmas.

In this section, we prove Lemma 4.3, Lemma 4.4 and Lemma 4.5.

5.1. Proof of the Lemma 4.3. The first claim of this lemma is easily checked.

We show the second part of the lemma.

- The case $P^{1,1,1;l_1,l_2}_a \neq (\emptyset)_k$.

In this case, component length vector
\[ w(P^{1,1,1;l_1,l_2}_a) = e_{l_1} + e_{l_2} \]
where $e_j = (0, \ldots, 0, 1, 0, \ldots, 0)$. On the other hand
\[ w(\emptyset)_k = 0. \]

So we obtain $P^{1,1,l_1,l_2}_a \not\simeq (\emptyset)_k$.

- The case $P^{3,l}_a \not\simeq (\emptyset)_k$.

By the Theorem 2.1, $a^3 = a a a$ with $a \neq \tau(a)$ is not homotopic to empty nanoword $\emptyset$. Combining this fact and Lemma 4.2, we obtain $P^{3,l}_a \not\simeq (\emptyset)_k$.

- The case $P^{2,1,l_1,l_2}_a \not\simeq (\emptyset)_k$.

By Lemma 4.1, we can assume $\alpha = \{a, \tau(a)\}$. In this case
\[ T(P^{2,1,l_1,l_2}_a) = e_{l_1} \not= 0 \]
(both the case $a = \tau(a)$ and the case $a \neq \tau(a)$). So we obtain $P^{2,1,l_1,l_2}_a \not\simeq (\emptyset)_k$.

- The case $P^{1,2,l_1,l_2}_a \not\simeq (\emptyset)_k$.

In this case
\[ T(P^{1,2,l_1,l_2}_a) = e_{l_2} \not= 0 \]
(both the case $a = \tau(a)$ and the case $a \neq \tau(a)$). So we obtain $P^{1,2,l_1,l_2}_a \not\simeq (\emptyset)_k$.

- The case $P^{1,1,1,l_1,l_2,l_3}_a \not\simeq (\emptyset)_k$.

In this case
\[ l_{P^{1,1,1,l_1,l_2,l_3}_a}(l_1, l_2) = a \in \pi. \]

Note that $a$ is not equal to the unit element 1 in $\pi$. So we obtain $P^{1,1,1,l_1,l_2,l_3}_a \not\simeq (\emptyset)_k$.

Now we finished prove the lemma.

5.2. Proof of the Lemma 4.4. By Lemma 4.1, we can assume $\alpha = \{a, \tau(a), b, \tau(b)\}$.

Suppose $\hat{a} \neq \hat{b}$. Let $crs(\alpha/\tau) = \{a, b\}$ and $L = \{a\}$. Then
\[ U_L(P_{a}^{X_1;Y_1}) = P_{a}^{X_1;Y_1}. \]

On the other hand,
\[ U_L(P_{b}^{X_2;Y_2}) = (\emptyset)_k. \]

So by Lemma 4.3, we obtain $P_{a}^{X_1;Y_1}$ is not homotopic to $P_{b}^{X_2;Y_2}$ for all $(X_1;Y_1), (X_2;Y_2) \in \{(1, 1; l_1, l_2), (3; l), (2, 1; l_1, l_2), (1, 2; l_1, l_2), (1, 1; l_1, l_2, l_3)\}$.

Suppose $\hat{a} = \hat{b}$. By the assumption $a$ is not equal to $b$, $Card(\hat{a}) = 2$ and $b = \tau(a)$.

- On $P^{1,1,l_1,l_2}_a \not\simeq P^{1,1,m_1,m_2}_{\tau(a)}$.

In this case
\[ l_{P^{1,1,l_1,l_2}_a}(l_1, l_2) = a. \]

On the other hand,
\[ l_{P^{1,1,m_1,m_2}_{\tau(a)}}(l_1, l_2) = \begin{cases} \tau(a) = a^{-1} (\text{if } (l_1, l_2) = (m_1, m_2)), \\ 1 (\text{otherwise}). \end{cases} \]

So $l_{P^{1,1,l_1,l_2}_a}(l_1, l_2)$ is not equal to $l_{P^{1,1,m_1,m_2}_{\tau(a)}}(l_1, l_2)$. So we obtain $P^{1,1,l_1,l_2}_a \not\simeq P^{1,1,m_1,m_2}_{\tau(a)}$.

- On $P^{1,1,l_1,l_2}_a \not\simeq P^{X;Y}_{\tau(a)}$ for all $(X;Y) \not= (1, 1; m_1, m_2)$.

In this case,
\[ w(P^{1,1,l_1,l_2}_a) = e_{l_1} + e_{l_2}, \]
On the other hand

So we obtain \( P_{\tau(a)}^{1,1,l_1,l_2} \neq P_{\tau(a)}^{X,Y} \).

- On \( P_{\tau(a)}^{3,l} \neq P_{\tau(a)}^{X,Y} \) for all \((X;Y) \neq (1,1;m_1,m_2)\).
  
  This is obtained from Theorem 2.1 and Lemma 4.2.

- On \( P_{\tau(a)}^{2,1,k,l_2} \neq P_{\tau(a)}^{X,Y} \) for all \((X;Y) \neq (1,1;m_1,m_2), (3;m)\).
  In this case,
  
  \[ l_{P_{\tau(a)}^{2,1,l_1,l_2}}(l_1,l_2) = a^2. \]

On the other hand

\[
l_{P_{\tau(a)}^{2,1,m_1,m_2}}(l_1,l_2) = \begin{cases} \tau(a)^2 = a^{-2} \ (\text{if } (l_1,l_2) = (m_1,m_2)), \\ 1 \ (\text{otherwise}) \end{cases},
\]

and

\[
l_{P_{\tau(a)}^{1,2,m_1,m_2}}(l_1,l_2) = \begin{cases} \tau(a)^2 = a^{-2} \ (\text{if } (l_1,l_2) = (m_1,m_2)), \\ 1 \ (\text{otherwise}) \end{cases},
\]

and

\[
l_{P_{\tau(a)}^{1,1,1,m_1,m_2,m_3}}(l_1,l_2) = \begin{cases} \tau(a) = a^{-1} \ (\text{if } \exists (m_i,m_j) = (l_1,l_2)), \\ 1 \ (\text{otherwise}) \end{cases}.
\]

So we obtain \( P_{\tau(a)}^{2,1,l_1,l_2} \neq P_{\tau(a)}^{X,Y} \).

- On \( P_{\tau(a)}^{2,1,l_1,l_2} \neq P_{\tau(a)}^{X,Y} \) for all \((X;Y) \neq (1,1;m_1,m_2), (3;m), (2,1;m_1,m_2)\).
  In this case,
  
  \[ l_{P_{\tau(a)}^{2,1,l_1,l_2}}(l_1,l_2) = a^2. \]

On the other hand

\[
l_{P_{\tau(a)}^{1,2,m_1,m_2}}(l_1,l_2) = \begin{cases} \tau(a)^2 = a^{-2} \ (\text{if } (l_1,l_2) = (m_1,m_2)), \\ 1 \ (\text{otherwise}) \end{cases},
\]

and

\[
l_{P_{\tau(a)}^{1,1,1,m_1,m_2,m_3}}(l_1,l_2) = \begin{cases} \tau(a) = a^{-1} \ (\text{if } \exists (m_i,m_j) = (l_1,l_2)), \\ 1 \ (\text{otherwise}) \end{cases}.
\]

So we obtain \( P_{\tau(a)}^{1,2,l_1,l_2} \neq P_{\tau(a)}^{X,Y} \).

- On \( P_{\tau(a)}^{1,1,1,l_1,l_2,l_3} \neq P_{\tau(a)}^{1,1,1,m_1,m_2,m_3} \).
  In this case
  
  \[ l_{P_{\tau(a)}^{1,1,1,l_1,l_2,l_3}}(l_1,l_2) = a, \]

and

\[
l_{P_{\tau(a)}^{1,1,1,m_1,m_2,m_3}}(l_1,l_2) = \begin{cases} \tau(a) = a^{-1} \ (\text{if } \exists (m_i,m_j) = (l_1,l_2)), \\ 1 \ (\text{otherwise}) \end{cases}.
\]

So we obtain \( P_{\tau(a)}^{1,1,1,l_1,l_2,l_3} \neq P_{\tau(a)}^{1,1,1,m_1,m_2,m_3} \).

Now we have completed the proof of Lemma 4.4.
5.3. Proof of the Lemma 4.5. • On $P_{\mu}^{1,1;l_1,l_2}$.

In this case

$$w(P_{\mu}^{1,1;l_1,l_2}) = e_{l_1} + e_{l_2},$$

and

$$w(P_{\mu}^{X,Y}) = 0$$

for all $(X;Y) \neq (1,1;m_1,m_2)$. So we obtain $P_{\mu}^{1,1;l_1,l_2} \simeq P_{\mu}^{X,Y}$ if and only if $(X;Y) = (1,1;l_1,l_2)$.

• On $P_{\tau}^{3;l}$.

By Theorem 2.1 and Lemma 4.2, We obtain $P_{\tau}^{3;l} \simeq P_{\tau}^{X,Y}$ if and only if $(X;Y) = (3;l)$.

• On $P_{\nu}^{2,1;l_1,l_2}$.

The case $P_{\nu}^{2,1;l_1,l_2} \neq P_{\nu}^{2,1;m_1,m_2}$ if $(l_1,l_2) \neq (m_1,m_2)$.

If $\alpha \neq \tau(\alpha)$, then

$$l_{P_{\nu}^{2,1;l_1,l_2}}(l_1,l_2) = a^2,$$

and

$$l_{P_{\nu}^{2,1;m_1,m_2}}(l_1,l_2) = 1 \neq a^2.$$ 

So we obtain $P_{\nu}^{2,1;l_1,l_2} \neq P_{\nu}^{2,1;m_1,m_2}$ if $(l_1,l_2) \neq (m_1,m_2)$.

If $\alpha = \tau(\alpha)$, then by Lemma 4.1 we can assume $\alpha = \{\alpha\}$. So we can use Gibson’s $S_0$ invariant. In this case

$$S_0(P_{\nu}^{2,1;l_1,l_2}) = (\emptyset, \cdots, l^1, e_{l_1}, \emptyset, \cdots, \emptyset),$$

and

$$S_0(P_{\nu}^{2,1;m_1,m_2}) = (\emptyset, \cdots, l^{m_1}, e_{m_2}, \emptyset, \cdots, \emptyset).$$

So we obtain $P_{\nu}^{2,1;l_1,l_2} \neq P_{\nu}^{2,1;m_1,m_2}$ if $(l_1,l_2) \neq (m_1,m_2)$.

The case $P_{\nu}^{2,1;l_1,l_2} \neq P_{\nu}^{1,2;m_1,m_2}$.

If $\alpha \neq \tau(\alpha)$ and $(l_1,l_2) \neq (m_1,m_2)$, then

$$l_{P_{\nu}^{2,1;l_1,l_2}}(l_1,l_2) = a^2,$$

and

$$l_{P_{\nu}^{1,2;m_1,m_2}}(l_1,l_2) = 1.$$ 

If $\alpha \neq \tau(\alpha)$ and $(l_1,l_2) = (m_1,m_2)$, then

$$T(P_{\nu}^{2,1;l_1,l_2}) = e_{l_1},$$

and

$$T(P_{\nu}^{1,2;l_1,l_2}) = -e_{l_2}.$$ 

Since $l_1$ is not equal to $l_2$,

$$T(P_{\nu}^{2,1;l_1,l_2}) \neq T(P_{\nu}^{1,2;l_1,l_2}).$$ 

If $\alpha = \tau(\alpha)$,

$$S_0(P_{\nu}^{2,1;l_1,l_2}) = (\emptyset, \cdots, l^1, e_{l_1}, \emptyset, \cdots, \emptyset),$$

and

$$S_0(P_{\nu}^{1,2;m_1,m_2}) = (\emptyset, \cdots, l^{m_2}, e_{m_1}, \emptyset, \cdots, \emptyset).$$
So if $P_{a}^{2,1;l_{1},l_{2}} \simeq P_{a}^{1,2;m_{1},m_{2}}$, then $(l_{1},l_{2}) = (m_{2},m_{1})$. However this contradict the assumption $l_{1} < l_{2}$ and $m_{1} < m_{2}$. By the above, we obtain $P_{a}^{2,1;l_{1},l_{2}} \neq P_{a}^{1,2;m_{1},m_{2}}$.

The case $P_{a}^{2,1;l_{1},l_{2}} \neq P_{a}^{1,1;m_{1},m_{2},m_{3}}$.

In this case,

$$\text{lk}(P_{a}^{1,1;m_{1},m_{2},m_{3}}) = \begin{cases} (1, \cdots, 1, a^{2}, 1, \cdots, 1) & \text{(if } a \neq \tau(a) \text{)}, \\
(1, \cdots, 1) & \text{(if } a = \tau(a) \text{).} \end{cases}$$

On the other hand,

$$\text{lk}(P_{a}^{1,1;m_{1},m_{2},m_{3}}) = (1, \cdots, 1, a, 1, \cdots, 1, a, 1, \cdots, 1, a, 1, \cdots, 1).$$

So we obtain $\text{lk}(P_{a}^{2,1;l_{1},l_{2}}) \neq \text{lk}(P_{a}^{1,1;m_{1},m_{2},m_{3}})$. This implies $P_{a}^{2,1;l_{1},l_{2}} \neq P_{a}^{1,1;m_{1},m_{2},m_{3}}$.

• On $P_{a}^{2,1;l_{1},l_{2}}$.

This case proved similarly as the case on $P_{a}^{2,1;l_{1},l_{2}}$.

• On $P_{a}^{1,1;l_{1},l_{2},l_{3}}$.

In this case,

$$l_{P_{a}^{1,1;l_{1},l_{2},l_{3}}}(i,j) = \begin{cases} a & \text{(if } (i,j) = (l_{1},l_{2}), (l_{1},l_{3}), (l_{2},l_{3}) \text{)}, \\
1 & \text{(otherwise).} \end{cases}$$

So we obtain $P_{a}^{1,1;l_{1},l_{2},l_{3}} \simeq P_{a}^{1,1;m_{1},m_{2},m_{3}}$ if and only if $(l_{1},l_{2},l_{3}) = (m_{1},m_{2},m_{3})$.

Now we have completed the proof of Lemma 4.5.

References


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