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Enumeration of the distinct shuffles of permutations

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A shuffle of two words is a word obtained by concatenating the two original words in either order and then sliding any letters from the second word back past letters of the first word, in such a way that the letters of each original word remain spelled out in their original relative order. Examples of shuffles of the words 1234 and 5678 are, for instance, 15236784 and 51236748. In this paper, we enumerate the distinct shuffles of two permutations of any two lengths, where the permutations are written as words in the letters $1, 2, 3, \dots, m$ and $1, 2, 3, \dots, n$, respectively.

Keywords: shuffles, permutations, enumeration, Catalan numbers, Shuffle Algebra

1 Introduction

Mathematicians have recently studied several notions of ‘shuffling’, including shuffling of a deck of cards (see [Aldous & Diaconis (1986)][Bayer & Diaconis (1992)] [Diaconis (1988)] [Diaconis (2002)] [Diaconis et al. (1983)] [Trefethen & Trefethen (2002)] [van Zuylen & Schalekamp (2004)]), ‘shuffling’ algorithms, such as the Fisher-Yates shuffle (also known as the Knuth shuffle) that generate random permutations of a finite set (see [Fisher & Yates (1948)] [Knuth (1973)] [Knuth (1998)]), and the perfect shuffle permutation (see [Diaconis et al. (1983)] [Ellis et al. (2000)] [Mevedoff & Morrison (1987)]).

We shall be interested in *shuffles of words*, where a *word* is defined to be a finite string of elements (known as *letters*) of a given set (known as an *alphabet*); in general repetitions of letters are allowed. We define the *length* of a word $u = a_1 \dots a_m$ to be $l(u) = m$ and the *support* of u to be $\text{supp}(u) = \{a_1, \dots, a_m\}$. A *subword* x of a word u is defined to be a word obtained by crossing out a (possibly empty) subset of the letters of u .

For example, for the alphabet $\mathcal{A} = \{1, 2, 3, 5, 7\}$, the words $u = 25372$ and $v = 123$ have supports $\text{supp}(u) = \{2, 3, 5, 7\}$ and $\text{supp}(v) = \{1, 2, 3\}$, and lengths $l(u) = 5$ and $l(v) = 3$. Two subwords of u are 232 and 537.

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2 Shuffles of Words

Given two words $u = a_1a_2 \dots a_m$ and $v = b_1b_2 \dots b_n$ in some alphabet \mathcal{A} , we obtain a *shuffle* of u and v by concatenating u and v to get

$$c_1c_2 \dots c_{m+n} = a_1a_2 \dots a_mb_1b_2 \dots b_n \quad (1)$$

and then permuting letters in such a way to achieve

$$w = c_{\rho(1)}c_{\rho(2)} \dots c_{\rho(m+n)}, \quad (2)$$

for some permutation $\rho \in \mathfrak{S}_{m+n}$ on $m+n$ letters satisfying the order-preserving conditions

$$\rho^{-1}(1) < \rho^{-1}(2) < \dots < \rho^{-1}(m) \quad (3)$$

and

$$\rho^{-1}(m+1) < \rho^{-1}(m+2) < \dots < \rho^{-1}(m+n). \quad (4)$$

In other words, we intersperse the letters of u with those of v to get w in such a way that the subword obtained by restricting w to the letters that came from u is simply u itself (and similarly for the subword obtained by restriction to the letters of v). Two different shuffles of the words 1234 and 5678 are, for instance, 15236784 and 51236748.

In the literature, the shuffle w is sometimes denoted by $u \sqcup\sqcup v$ (see [Hersh (2002)]). Since $\sqcup\sqcup$ depends on a choice of ρ , however, and since $u \sqcup\sqcup v$ sometimes denotes instead the *shuffle product* of u and v in the *shuffle algebra* (see [Reutenauer (1993)], page 24), we will use the notation $\sqcup\sqcup_\rho$ to avoid ambiguity. We define

$$\mathfrak{sh}(u, v) = \{u \sqcup\sqcup_\rho v \mid \rho \in \mathfrak{S}_{m+n} \text{ satisfies (3) and (4)}\} \quad (5)$$

to be the set of all shuffles of u with v . For ease of reference, we shall also set

$$\mathfrak{S}_{m,n} = \{\rho \in \mathfrak{S}_{m+n} \mid \rho \text{ satisfies (3) and (4)}\}. \quad (6)$$

The *shuffle algebra* \mathfrak{A} (see [Crossley (2006)] [Ehrenborg (1996)] [Reutenauer (1993)]), a commutative Hopf algebra structure on the free \mathbb{Z} -module generated by finite words in a given alphabet \mathcal{A} , has as multiplication the *shuffle product* Δ , which is given by

$$\Delta(u \otimes v) = \sum_{w \in \mathfrak{sh}(u,v)} \mu_w w \quad (7)$$

for words u and v , where

$$\mu_w = \#\{\rho \in \mathfrak{S}_{l(u),l(v)} \mid u \sqcup\sqcup_\rho v = w\} \quad (8)$$

is the multiplicity of w . The shuffle algebra has applications, for instance, in number theory: the multiplication of two multiple zeta values can be expressed as the sum of other multiple zeta values via a shuffle relation or a quasi-shuffle (stuffle) relation (see [Guo & Xie (2008)] [Ihara et al. (2006)]).

We can define, analogously, a shuffle of k words (or k -shuffle) to be a permutation of the concatenation of k words (with lengths n_1, n_2, \dots, n_k) in such a way that the inverse permutation preserves order when restricted to the index subsets $[n_1], [n_1 + 1, n_1 + n_2], \dots, [n_1 + n_2 + \dots + n_{k-1} + 1, n_1 + n_2 + \dots + n_k]$, where the interval notation $[n_1 + 1, n_1 + n_2]$ denotes the set of integers from $n_1 + 1$ to $n_1 + n_2$. A k -shuffle is also sometimes referred to as an α -shuffle, where $\alpha = (n_1, n_2, \dots, n_k) \in \mathbb{P}^k$ is any k -tuple of positive integers. (But we reserve the notation \sqcup_ρ for 2-shuffles, as they are the main focus of our research.)

Shuffles of words arise in several contexts. For instance, given a subset

$$T = \{s_1, s_2, \dots, s_{k-1}\} \subseteq [n - 1], \tag{9}$$

it can be seen that a permutation $\tau \in \mathfrak{S}_n$ is a k -shuffle of the sets $[s_1], [s_1 + 1, s_2], \dots, [s_{k-2} + 1, s_{k-1}], [s_{k-1} + 1, n]$ if and only if the descent set $D(\tau^{-1})$ of the inverse permutation is a subset of T (see [Stanley (1997)], page 70). Shuffles appear in the representation theory of finite groups; the left cosets of the Young Subgroup $\mathfrak{S}_{\alpha_1} \times \mathfrak{S}_{\alpha_2} \times \dots \times \mathfrak{S}_{\alpha_k}$ in the Symmetric Group \mathfrak{S}_n (where $n = \sum_{j=1}^k \alpha_j$) correspond exactly to the unique α -shuffles associated with $\alpha = (\alpha_1, \alpha_2, \dots, \alpha_k)$ (see [Stanley (1999)], page 351).

Shuffles play a role in the multiplication of fundamental quasisymmetric functions L_γ ; in fact, if $u \in \mathfrak{S}_m$ and $v \in \mathfrak{S}_{[m+1, m+n]}$, then

$$L_{\text{co}(u)}L_{\text{co}(v)} = \sum_{w \in \text{sh}(u, v)} L_{\text{co}(w)}, \tag{10}$$

where $\text{co}(u)$ denotes the composition associated with the descent set $D(u)$ (see [Stanley (1999)], page 482, exercise 7.93). Moreover, shuffle posets on the words u and v can be defined by considering the set of subwords of all possible shuffles of u with v , taking u as the minimal element, v as the maximal element, and defining the cover relation to be $x \prec y$ if y can be obtained from x either by deleting one letter of u or inserting one letter of v . Greene [Greene (1988)] introduced shuffle posets, and Doran [Doran (2002)] and Hersh [Hersh (2002)] generalized them (see also [Ehrenborg (1996)] [Simion & Stanley (1999)]).

3 The Main Question

A natural question to ask is how to enumerate the *distinct* shuffles of words.

Question 1 *Given words u and v , how many distinct shuffles are there of u with v ?*

Assuming m and n to be the lengths of u and v , respectively, note that if $\text{supp}(u) \cap \text{supp}(v) = \emptyset$, then there are $\binom{m+n}{m}$ distinct shuffles (all shuffles are distinct).

Observation 2 *For any given words u and v , we can define an equivalence relation on $\mathfrak{S}_{\text{l}(u), \text{l}(v)}$ by $\rho \sim \tau$ if $u \sqcup_\rho v = u \sqcup_\tau v$.*

The equivalence relation is nontrivial only when $\text{supp}(u) \cap \text{supp}(v) \neq \emptyset$. So one could reformulate Question 1 to ask how many different equivalence classes are induced on $\mathfrak{S}_{\text{l}(u), \text{l}(v)}$ by shuffling a given u with a given v .

In various applications of shuffles, the supports of the words are usually assumed to be disjoint, but we investigate the consequences of discarding this assumption while seeking an answer to Question 1.

We resolve this question for the important case where the words u and v are assumed to be permutations on the letters $\{1, 2, 3, \dots, m\}$ and $\{1, 2, 3, \dots, n\}$, respectively. Our answer is given by the following theorem, for which we shall give details in Section 5 below.

Theorem 3 *The number of distinct shuffles of a permutation $\alpha \in \mathfrak{S}_m$ with a permutation $\beta \in \mathfrak{S}_n$, with $m \leq n$, is given by the following formula:*

$$\#\mathfrak{sh}(\alpha, \beta) = \sum_{k=0}^{\lfloor \frac{m}{2} \rfloor} \sum_{\mathbf{a}=\{0=a_0 < a_1 < \dots < a_{2k} < a_{2k+1}=m+1\}} (-1)^{h(\mathbf{a})} F_{\sigma}(\mathbf{a}), \quad (11)$$

where $\sigma = \bar{\alpha}^{-1} \circ \beta$, $\bar{\alpha} \in \mathfrak{S}_n$ is the natural extension of α , and $F_{\sigma}(\mathbf{a})$ is a product of determinants which enumerate the shuffles on a ‘local’ level.

For an explanation of the notation used and a description of the determinants involved, see Section 5 below.

4 Enumeration of the Distinct Shuffles of Permutations

We shall start by enumerating shuffles of the identity permutation with itself.

Proposition 4 *The number of distinct shuffles of the identity permutation on n letters with itself is the n^{th} Catalan number C_n , that is*

$$\#\mathfrak{sh}(\text{id}_n, \text{id}_n) = \frac{1}{n+1} \binom{2n}{n}. \quad (12)$$

Proof: A straightforward proof entails showing that set of shuffles of id_n with itself corresponds bijectively with the set of ballot sequences of length $2n$ (which is known to have cardinality C_n). For a given $w \in \mathfrak{sh}(\text{id}_n, \text{id}_n)$, simply substitute a 1 for the first occurrence of each integer between 1 and n , and a -1 for the second occurrence to get a ballot sequence of length $2n$ (that is, a sequence of n ones and n minus ones whose partial sums are all nonnegative). \square

It is possible to show the following formula for the number of distinct shuffles of the identity in two different lengths.

Proposition 5 *For $m \neq n$, the number of distinct shuffles of the identity permutation on m letters with the identity permutation on n letters is given by*

$$\#\mathfrak{sh}(\text{id}_m, \text{id}_n) = \sum_{r=0}^{\lfloor \frac{n-m}{2} \rfloor} (-1)^r \binom{n-m-r}{r} C_{n-r}. \quad (13)$$

We get Proposition 5 from the following recursion for shuffles of the identity in two different lengths.

Lemma 6 *For $m \neq n$, the number of distinct shuffles of the identity permutation on m elements with the identity permutation on n elements is determined by*

$$\#\mathfrak{sh}(\text{id}_m, \text{id}_n) = \#\mathfrak{sh}(\text{id}_{m-1}, \text{id}_n) + \#\mathfrak{sh}(\text{id}_m, \text{id}_{n-1}). \quad (14)$$

Proof: Lemma 6 is easily verified by considering the bijection

$$\gamma : \mathfrak{sh}(\text{id}_m, \text{id}_n) \rightarrow \mathfrak{sh}(\text{id}_{m-1}, \text{id}_n) \cup \mathfrak{sh}(\text{id}_m, \text{id}_{n-1})$$

given by dropping the last letter of each $w \in \mathfrak{sh}(\text{id}_m, \text{id}_n)$ to get either $\gamma(w) \in \mathfrak{sh}(\text{id}_{m-1}, \text{id}_n)$ or $\gamma(w) \in \mathfrak{sh}(\text{id}_m, \text{id}_{n-1})$. As long as $m \neq n$, we have $\mathfrak{sh}(\text{id}_{m-1}, \text{id}_n) \cap \mathfrak{sh}(\text{id}_m, \text{id}_{n-1}) = \emptyset$. \square

More generally, for $m \leq n$ and any $\alpha \in \mathfrak{S}_m$ and $\beta \in \mathfrak{S}_n$, it can be assumed without loss of generality that $\alpha = \text{id}_m$, due to the following fact.

Fact 7 For any $m \leq n$ and any $\alpha \in \mathfrak{S}_m$, $\beta \in \mathfrak{S}_n$, we have

$$\#\mathfrak{sh}(\alpha, \beta) = \#\mathfrak{sh}(\text{id}_m, (\bar{\alpha})^{-1} \circ \beta), \quad (15)$$

where $\bar{\alpha} \in \mathfrak{S}_n$ is the natural extension of α to a permutation on n letters.

Here we are simply reordering the alphabet $\mathcal{A} = [m]$ so that α now behaves like the identity permutation id_m on the reordered alphabet. It is also easy to note that $\#\mathfrak{sh}$ is symmetric: $\#\mathfrak{sh}(u, v) = \#\mathfrak{sh}(v, u)$ is true for any words u and v (they need not be permutations).

Now let the reverse permutation word $n, n-1, \dots, 2, 1$ be denoted by rev_n . The following result can be shown via a bijective proof.

Proposition 8

$$\#\mathfrak{sh}(\text{id}_m, \text{rev}_n) = \binom{m+n}{m} - \binom{m+n-2}{m-1}. \quad (16)$$

Proof: To verify Proposition 8, simply note that for each $w \in \mathfrak{sh}(\text{id}_m, \text{rev}_n)$, we have either $\mu_w = 2$ or $\mu_w = 1$. (Either w has a pair of double elements, or it doesn't.)

Consider the map $\kappa : \{w \in \mathfrak{sh}(\text{id}_m, \text{rev}_n) \mid \mu_w = 2\} \rightarrow \mathfrak{sh}(+^{m-1}, -^{n-1})$ that sends each duplicated shuffle w to a sequence $\kappa(w) \in \mathfrak{sh}(+^{m-1}, -^{n-1})$ obtained by excising the double elements and then sending each letter from id_m to a $+$ and each letter from rev_n to a $-$. For example, for $1243321 \in \mathfrak{sh}(123, 4321)$, obtain $\kappa(1243321)$ by excising 33 to get 12421 . Then replace elements with pluses and minuses to get $++--$.

Noting that $\#\mathfrak{sh}(+^{m-1}, -^{n-1}) = \binom{(m-1)+(n-1)}{m-1}$, we subtract this number of duplicates from $\binom{m+n}{m}$, the total number of shuffles, counted with multiplicity, of words of lengths m and n . \square

5 The Main Theorem

Let us now enumerate the number of shuffles of the identity on m letters with any permutation $\sigma \in \mathfrak{S}_n$ (throughout, we shall assume without loss of generality that $m \leq n$). We shall first provide some terminology and motivation and then state the main theorem.

Let us call a subword x obtained from any word u *consecutive* if the letters of x appear consecutively in u . For instance, 364 is a consecutive subword of 136425 . We call a shuffle $w \in \mathfrak{sh}(\text{id}_n, \text{id}_n)$ *indecomposable* if there is no consecutive subword w' of w such that $w' \in \mathfrak{sh}(\text{id}_k, \text{id}_k)$ for some $1 \leq k < n$. For ease of notation, let

$$\text{ind}\mathfrak{c}(x) = \{\text{indecomposable shuffles of } x \text{ with itself}\}. \quad (17)$$

Observe that, when a shuffle w has multiplicity $\mu_w > 1$, this occurs because some consecutive subword x of σ is in fact a string of consecutive elements in the alphabet of w ; we call such a subword of σ an *embedded identity subword*. On the local level we then have, embedded in w , a shuffle of the identity permutation on a consecutive subset of the intersection of the given alphabets with itself. That is,

$$w = \cdots * (x \sqcup_{\eta} x) * \cdots \quad (18)$$

for some $\eta \in \mathfrak{S}_{l(x), l(x)}$, where $*$ denotes concatenation. We shall denote the set of embedded identity subwords of σ as

$$\text{idsub}(\sigma) = \{\text{embedded identity subwords of } \sigma\}. \quad (19)$$

If id_4 is shuffled with 52341, for example, we can obtain the shuffle

$$512342341 \in \{51 * (234 \sqcup_{\eta} 234) * 1 \mid \eta \in \mathfrak{S}_{3,3}\}, \quad (20)$$

which has multiplicity 2 because the local shuffle $234234 \in \mathfrak{sh}(234, 234)$ is indecomposable and can be obtained in exactly two ways, whereas there are no additional ways of obtaining the global shuffle $512342341 \in \mathfrak{sh}(\text{id}_4, 52341)$.

We say that a set $X = \{x_1, \dots, x_r\}$ of embedded identity subwords of a permutation is *compatible* if the x_i have pairwise disjoint supports and if there exists some shuffle $w \in \mathfrak{sh}(\text{id}_m, \sigma)$ in which each of the x_i is locally shuffled with itself. For instance, $\{23, 45\}$ is a set of compatible embedded identity subwords of 23145 because in the shuffle $1232314455 \in \mathfrak{sh}(\text{id}_5, 23145)$ both 23 and 45 are locally shuffled with themselves.

Given a permutation word u and a compatible set $X = \{x_1, \dots, x_j\}$ of embedded identity subwords of u , note that u is the concatenation $u = g_0 * x_1 * g_1 * \cdots * x_j * g_j$ for some consecutive subwords g_0, g_1, \dots, g_j of u whose supports are pairwise disjoint. We say that the g_i are the subwords of u *cut out* by the set X .

For instance, in the permutation 23145, the set $\{23, 45\}$ cuts out the subwords \square , 1, and \square (where \square denotes the empty word). Likewise, for the permutation word 52341, the set $\{23, 4\}$ cuts out the subwords 5, \square , and 1.

Proposition 9 *For $\sigma \in \mathfrak{S}_n$ and any $w \in \mathfrak{sh}(\text{id}_m, \sigma)$, we have $\mu_w = 2^t$ for some integer $t \geq 0$, where t is the maximal number of compatible embedded identity permutation subwords in σ that are locally shuffled with themselves in w .*

To illustrate this statement, we can see that for $311223 \in \mathfrak{sh}(\text{id}_3, 312)$, we have $\mu(311223) = 4$ and $t = 2$. The embedded identity subwords that are locally shuffled with themselves in 311223 are 1, 2, and 12; but $\{1, 2\}$ is the largest set of such subwords that is compatible. In general, we shall call the integer $t = \text{dup}(w)$ the *number of sites of duplication* in w . Moreover, we shall set $N_t^\sigma = \#\{w \in \mathfrak{sh}(\text{id}_m, \sigma) \mid \text{dup}(w) = t\}$.

We can actually enumerate $\#\mathfrak{sh}(\text{id}_m, \sigma)$ by applying the Inclusion-Exclusion principle. First we take the total number of shuffles counted with multiplicity, and then alternately subtract and add the cardinalities of certain subsets counted with multiplicity until we arrive at a count of the total number of shuffles without multiplicity.

Indeed,

$$\#\mathfrak{sh}(\text{id}_m, \sigma) = \binom{m+n}{m} + \sum_{j=1}^m (-1)^j T_j^\sigma, \quad (21)$$

where $T_j^\sigma = \sum_{t=j}^m \binom{t}{j} 2^{t-j} N_t^\sigma$.

Observation 10 T_j^σ is the number of (not necessarily distinct shuffles) in $\mathfrak{sh}(\text{id}_m, \sigma)$ with j or more sites of duplication, enumerated by choosing a j -element subset $X = \{x_1, \dots, x_j\}$ of compatible embedded identity permutation subwords of σ and assuming, in turn, that each element $x_i \in X$ is shuffled locally and indecomposably with itself, then counting with multiplicity all local shuffles of each subword of id_m cut out by X with the corresponding subword of σ also cut out by X .

That is, T_j^σ can be computed as

$$T_j^\sigma = \sum_{\text{compatible } \{x_1, \dots, x_j\} \subseteq \text{idsub}(\sigma)} \binom{l(f_0) + l(g_0)}{l(f_0)} \cdot \#\text{indc}(x_1) \cdot \binom{l(f_1) + l(g_1)}{l(f_1)} \cdots \cdot \#\text{indc}(x_j) \cdot \binom{l(f_j) + l(g_j)}{l(f_j)}, \quad (22)$$

where the f_i and g_i are the subwords of id_m and of σ , respectively, that are cut out by the set $\{x_1, \dots, x_j\}$. Recall that the number of local shuffles of f_i with g_i counted with multiplicity is $\binom{l(f_i) + l(g_i)}{l(f_i)}$.

In the example of $\mathfrak{sh}(\text{id}_3, 312)$, we can compute

$$T_1^{312} = \binom{1}{0} \cdot C_0 \cdot \binom{3}{2} + \binom{3}{1} \cdot C_0 \cdot \binom{1}{1} + \binom{2}{2} \cdot C_0 \cdot \binom{2}{0} + \binom{1}{0} \cdot C_1 \cdot \binom{1}{1} = 8 \quad (23)$$

because we can fix first double 1's to count shuffles of the form $(\square \sqcup_{\rho_1} 3) * 11 * (23 \sqcup_{\rho_2} 2)$, then fix double 2's to count those of the form $(1 \sqcup_{\rho_3} 31) * 22 * (3 \sqcup_{\rho_4} \square)$, next, fix double 3's to count shuffles of the form $(12 \sqcup_{\rho_5} \square) * 33 * (\square \sqcup_{\rho_6} 12)$, and lastly, fix the unique indecomposable shuffle of 12 with itself to count those of the form $(\square \sqcup_{\rho_7} 3) * 1212 * (3 \sqcup_{\rho_8} \square)$. Note that in each case the local identity shuffle we fix (such as 11 or 1212) is indecomposable, and so the factor C_{k-1} counts the distinct indecomposable shuffles of a local identity subword of length k with itself. Similarly,

$$T_2^{312} = \binom{1}{0} \cdot C_0 \cdot \binom{0}{0} \cdot C_0 \cdot \binom{1}{1} = 1, \quad (24)$$

as we can see by counting shuffles of the form $(\square \sqcup_{\rho_9} 3) * 11 * (\square \sqcup_{\rho_{10}} \square) * 22 * (3 \sqcup_{\rho_{11}} \square)$, whereas $T_3^{312} = 0$ because there is no compatible 3-subset of embedded identity permutation subwords, and so

$$\#\mathfrak{sh}(\text{id}_3, 312) = \binom{3+3}{3} - 8 + 1 - 0 = 13. \quad (25)$$

We will use the notation $z_{i,j}^\sigma$ to denote the number of local shuffles counted with multiplicity of the subword a occurring between (and not including) the letters $i < j$ in id_m with the subword b occurring

between the letters $i < j$ in σ . That is, if such words a and b exist, then we have $z_{i,j}^\sigma = \binom{l(a)+l(b)}{l(a)}$; otherwise, $z_{i,j}^\sigma = 0$. For example, $z_{0,2}^{312} = \binom{3}{1} = 3$, $z_{1,2}^{312} = \binom{0}{0} = 1$, and $z_{1,3}^{312} = 0$.

We use $z_{i,j}^\sigma$ to construct a square matrix with all ones on the subdiagonal and all zeros below the subdiagonal. For entries on or above the diagonal, $z_{i,j}^\sigma$ keeps track of whether or not i and j are inverted in σ , and if they are not inverted, $z_{i,j}^\sigma$ takes on the value of the total number of possible ways of shuffling the letters between paired occurrences of i and j , including any repeated shuffles.

By defining a matrix $Z_{c,d}^\sigma = [z_{i,j}^\sigma]_{c \leq i \leq d-1, c+1 \leq j \leq d}$ below and taking its determinant, we are taking an alternating sum that systematically looks for compatible sets of letters (that is, compatible length 1 embedded identity subwords of σ) that occur between the letters c and d (not including c and d themselves). When the set of letters, say $\{b_1, b_2, \dots, b_q\}$, is compatible, then we get a nonzero term of absolute value $z_{c,b_1}^\sigma \cdot z_{b_1,b_2}^\sigma \cdots z_{b_q,m+1}^\sigma$.

For example,

$$Z_{0,4}^{312} = \begin{pmatrix} 1 & 3 & 1 & 20 \\ 1 & 1 & 0 & 3 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \end{pmatrix}. \quad (26)$$

For $1 \leq e < f \leq m$, if the word $e, e+1, \dots, f$ is a simultaneous consecutive subword for id_m and σ , we will say that $\theta^\sigma(e, f)$ denotes the number of indecomposable local shuffles of the word $e, e+1, \dots, f$ with itself; otherwise we will set $\theta^\sigma(e, f) = 0$. The purpose of the $y_{i,j}^\sigma$ below is to construct this function $\theta^\sigma(e, f)$ by defining a matrix $Y_{e,f}^\sigma = [y_{i,j}^\sigma]_{e \leq i, j \leq f-1}$ in such a way that $\theta^\sigma(e, f) = \det Y_{e,f}^\sigma$.

For example,

$$Y_{1,3}^{312} = \begin{pmatrix} C_0 & C_1 \\ 0 & 0 \end{pmatrix}, \quad (27)$$

whereas

$$Y_{1,2}^{312} = (C_0) \quad (28)$$

and

$$Y_{2,3}^{312} = (0). \quad (29)$$

The subsets $\mathbf{a} = \{0 = a_0 < a_1 < \dots < a_{2k} < a_{2k+1} = m+1\} \subseteq [0, m+1]$ below determine the endpoints of the subwords $a_1 \dots a_2, a_3 \dots a_4$, through $a_{2k-1} \dots a_{2k}$ of id_m , each of which has length greater than one and may possibly be an embedded identity subword for σ . The exponent $h(\mathbf{a})$ ensures the correct sign for purposes of applying the principle of Inclusion-Exclusion.

We are now ready for the main theorem.

Theorem 11 (Theorem 3, restated in detail)

$$\#\text{sh}(\text{id}_m, \sigma) = \sum_{k=0}^{\lfloor \frac{m}{2} \rfloor} \sum_{\mathbf{a}=\{0=a_0 < a_1 < \dots < a_{2k} < a_{2k+1}=m+1\}} (-1)^{h(\mathbf{a})} \prod_{r=0}^k \det Z_{a_{2r}, a_{2r+1}}^\sigma \prod_{s=1}^k \det Y_{a_{2s-1}, a_{2s}}^\sigma, \quad (30)$$

where

$$h(\mathbf{a}) = m - \sum_{t=1}^k (a_{2t} - a_{2t-1}), \quad (31)$$

and we define the matrices

$$Z_{c,d}^\sigma = [z_{i,j}^\sigma]_{c \leq i \leq d-1, c+1 \leq j \leq d}, \quad (32)$$

with

$$z_{i,j}^\sigma = \begin{cases} 0, & i > j \\ 1, & i = j \\ 0, & 0 < i < j < m+1 \text{ and } \sigma^{-1}(i) > \sigma^{-1}(j) \\ \binom{j-i-1+\sigma^{-1}(j)-\sigma^{-1}(i)-1}{j-i-1}, & 0 < i < j < m+1 \text{ and } \sigma^{-1}(i) < \sigma^{-1}(j) \\ \binom{j-1+\sigma^{-1}(j)-1}{j-1}, & i = 0, j < m+1 \\ \binom{m-i+n-\sigma^{-1}(i)}{m-i}, & j = m+1, i > 0 \\ \binom{m+n}{m}, & i = 0, j = m+1, \end{cases} \quad (33)$$

and the matrices

$$Y_{e,f}^\sigma = [y_{i,j}^\sigma]_{e \leq i, j \leq f-1}, \quad (34)$$

with

$$y_{i,j}^\sigma = \begin{cases} 0, & i - j > 1 \text{ or } \sigma^{-1}(i+1) \neq \sigma^{-1}(i) + 1 \\ -1, & i - j = 1 \text{ and } \sigma^{-1}(i+1) = \sigma^{-1}(i) + 1 \\ C_{j-i}, & i \leq j \text{ and } \sigma^{-1}(i+1) = \sigma^{-1}(i) + 1 \end{cases} \quad (35)$$

where

$$C_{j-i} = \frac{1}{j-i+1} \binom{2(j-i)}{j-i}, \text{ the } (j-i)^{\text{th}} \text{ Catalan number.} \quad (36)$$

While equation (30) may look unwieldy, it is relatively easy to write a computer algorithm for Maple that will calculate the number of distinct shuffles of any two permutations. If at least one of the permutations has length bounded by 13, the processor on a laptop can easily handle the calculation. Examples of calculations include $\#\mathfrak{sh}(\text{id}_3, 321) = 14$, $\#\mathfrak{sh}(\text{id}_2, 3421) = 11$, $\#\mathfrak{sh}(2431, 1432) = 44$, $\#\mathfrak{sh}(\text{id}_6, 126354) = 374$, and if $\sigma = 7, 8, 9, 10, 11, 12, 13, 1, 2, 3, 4, 5, 6 \in \mathfrak{S}_{13}$, then $\#\mathfrak{sh}(\text{id}_{13}, \sigma) = 10104590$.

6 Future Directions

Open problems related to the work in this paper include the following projects:

6.1 Enumerating Distinct Shuffles of Multiset Permutations

Compute the number of distinct shuffles of any two multiset permutations; for example, $\#\mathfrak{sh}(12322, 33214)$. This is a significant generalization of the current problem, because the possible ways that duplications in such shuffles can occur are much more complicated than with ordinary permutations, and multiplicities of shuffles no longer need to be powers of 2. We believe, however, that once we can classify the types of multiplicities that can occur the problem will become tractable, and that the intuitions gained in solving the current problem will help me to reach that point.

6.2 Enumerating Distinct k -Shuffles of Permutations

Compute the number of distinct k -shuffles of k permutations of any k lengths, where k is any positive integer; for example, $\#\mathfrak{sh}(132, 231, 1324)$. This is another important generalization. Again, multiplicities need not be powers of 2; rather, they appear to be related to products of factorials, but it is not yet clear how exactly to compute them. It seems that making progress on counting shuffles of multiset permutations should give insight into what occurs with k -shuffles of ordinary permutations; observe that $\#\mathfrak{sh}(132, 231, 1324)$ is equal to $\sum_{w \in \mathfrak{sh}(132, 231)} \#\mathfrak{sh}(w, 1324)$ minus a certain number of shuffles y such that $y \in \mathfrak{sh}(w, 1324) \cap \mathfrak{sh}(w', 1324)$ for some $w' \neq w \in \mathfrak{sh}(132, 231)$. Note that w and w' can be thought of as multiset permutations.

6.3 Deducing Monotonicity Results

Deduce monotonicity results for the number of distinct shuffles on permutation groups. Such results would help to clarify the meaning of the formula given in Theorem 11. For $1 \leq n \leq 6$, the minimal number of distinct shuffles of a permutation with the identity permutation of the same length is C_n , achieved by identity permutation (see Proposition 4). We conjecture that this is the case for all n .

For $n = 1, 2, 3$, the maximal number of shuffles of a permutation with the identity is achieved by the reverse permutation. For $n = 4, 5, 6$, however, the maximal number of distinct shuffles with the identity is achieved by the halfway-shifted permutations 3412, 34512, and 456123, respectively. Together, these cases give the first six terms of the sequence of maximal shuffle counts: 1, 4, 14, 54, 197, 792 (now catalogued as sequence A145211 in the On-Line Encyclopedia of Integer Sequences; see also sequence A145208). We would like to extend this sequence and to determine whether, as we conjecture, maximality is actually achieved by the halfway-shifted permutations for all $n \geq 4$.

Indeed, we would like more generally to find a poset structure on \mathfrak{S}_n for which the function $\sigma \mapsto \#sh(\text{id}_n, \sigma)$ is always monotone increasing. The Bruhat order fails to provide such a structure for $n = 4, 5, 6$, but perhaps a modification of the Bruhat order would provide the desired poset structure.

6.4 Enumerating Distinct Shuffles according to Permutation Statistics

Enumerate distinct shuffles according to various permutation statistics, such as descent sets, number of inversions, or major index. Enumeration by statistics could yield insights into the above problems and refine our current results.

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