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# Permutation Pattern matching in (213, 231)-avoiding permutations

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Given permutations  $\sigma$  of size  $k$  and  $\pi$  of size  $n$  with  $k < n$ , the *permutation pattern matching* problem is to decide whether  $\sigma$  occurs in  $\pi$  as an order-isomorphic subsequence. We give a linear-time algorithm in case both  $\pi$  and  $\sigma$  avoid the two size-3 permutations 213 and 231. For the special case where only  $\sigma$  avoids 213 and 231, we present a  $O(\max(kn^2, n^2 \log \log n))$ -time algorithm. We extend our research to bivincular patterns that avoid 213 and 231 and present a  $O(kn^4)$ -time algorithm. Finally we look at the related problem of the longest subsequence which avoids 213 and 231.

**Keywords:** Permutation Pattern matching

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## 1 Introduction

A permutation  $\sigma$  is said to *occur* in another permutation  $\pi$  (or  $\pi$  *contains*  $\sigma$ ), denoted  $\sigma \preceq \pi$ , if there exists a subsequence of elements of  $\pi$  that has the same relative order as  $\sigma$ . Otherwise,  $\pi$  is said to *avoid* the permutation  $\sigma$ . For example a permutation contains the permutation 123 (resp. 321) if it has an increasing (resp. a decreasing) subsequence of size 3. Similarly, 213 occurs in 6152347, but 231 does not occur in 6152347. During the last decade, the study of patterns in permutations has become a very active area of research [14] and a whole annual conference (PERMUTATION PATTERNS) focuses on patterns in permutations.

We consider here the so-called *permutation pattern matching* problem (also sometimes referred to as the *pattern involvement problem*): Given two permutations  $\sigma$  of size  $k$  and  $\pi$  of size  $n$ , the problem is to decide whether  $\sigma \preceq \pi$  (the problem is attributed to Wilf in [5]). The permutation pattern matching is known to be **NP**-hard [5]. It is however polynomial-time solvable by brute-force enumeration if  $\sigma$  has bounded size. Improvements to this algorithm were presented in [3] and [1], the latter describing a  $O(n^{0.47k+o(k)})$ -time algorithm. Bruner and Lackner [7] gave a fixed-parameter algorithm solving the permutation pattern matching problem with an exponential worst-case runtime of  $O(1.52^n \cdot n \cdot k)$ . This is an improvement upon the  $O(k \binom{n}{k})$  runtime required by brute-force search without imposing restrictions on  $\sigma$  and  $\pi$ , where one has to enumerate all the  $\binom{n}{k}$  different subsequences of size  $k$  in  $\pi$  and test if one of them has the same relative order as  $\sigma$ . Guillemot and Marx [10] showed that the permutation pattern matching problem is

solvable in  $2^{O(n \cdot k^2 \log k)}$ , and hence is fixed-parameter tractable with respect to the length  $k$  of the pattern  $\sigma$  (standard parameterization). However, Mach proved that the permutation involvement problem under the standard parameterization does not have a polynomial size kernel (assuming  $\text{NP} \not\subseteq \text{coNP}/\text{poly}$  [15]).

A few particular cases of the permutation pattern matching problem have been attacked successfully. The case of increasing patterns is solvable in  $O(n \log \log k)$ -time [8], improving the previous 30-year bound of  $O(n \log k)$ . Furthermore, the patterns 132, 213, 231, 312 can all be handled in linear-time by stack sorting algorithms. Any pattern of size 4 can be detected in  $O(n \log n)$  time [3]. Algorithmic issues for 321-avoiding patterns matching for permutations have been investigated in [11] and more recently in [2]. The permutation pattern matching problem is also solvable in polynomial-time for separable patterns [12, 5] (see also [6] for the longest common subsequence problem and related ones on separable permutations). Separable permutations are permutations that do not have an occurrence of 2413 nor 3142, and they are enumerated by the Schröder numbers.

(Notice that the separable permutations include as a special case the stack-sortable permutations, which avoid the pattern 231.) The major negative result is given in [13]. They prove that the permutation pattern matching problem is **NP**-complete when  $\sigma$  has no decreasing subsequence of length 3 and  $\pi$  has no decreasing subsequence of length 4. This provides the first known example of the permutation pattern matching problem being hard when one or both of  $\pi$  and  $\sigma$  are restricted to a proper hereditary class of permutations.

There exist many generalisations of patterns that are worth considering in the context of algorithmic issues in pattern matching (see [14] for an up-to-date survey). *Vincular patterns*, also called *generalized patterns*, resemble (classical) patterns with the additional constraint that some of the elements in a occurrence must be consecutive in positions. Of particular importance in our context, Bruner and Lackner [7] proved that deciding whether a vincular pattern  $\sigma$  of size  $k$  occurs in a longer permutation  $\pi$  is  $W[1]$ -complete for parameter  $k$ ; for an up-to-date survey of the  $W[1]$  class and related material, see [9]. *Bivincular patterns* generalize classical patterns even further than vincular patterns by adding a constraint on values.

We focus in this paper on pattern matching issues for *wedge permutations* (i.e., those permutations that avoid both 213 and 231). This paper is organized as follows. In Section 2 the needed definitions are presented. Section 3 is devoted to presenting an online linear-time algorithm in case both permutations are wedge permutations, whereas Section 4 focuses on the case where only the pattern is a wedge permutation. In Section 5 we give a polynomial-time algorithm for a bivincular wedge permutation pattern. In Section 6 we consider the problem of finding the longest wedge permutation pattern in permutations.

## 2 Definitions

A *permutation* of size  $n$  is a linear ordering of an ordered set of size  $n$ . When writing the permutation we omit the  $<$  sign, thus writing the permutation as a word:  $\pi = \pi_1 \pi_2 \dots \pi_n$ , whose elements are distinct and usually consist of the integers  $1, 2, \dots, n$ .

We need to consider both the natural order of the set and the linear order given by the permutation. When talking about an element, we refer to the relative position in the natural order of the set as its value and we refer to the relative position in the order given by the permutation as its position. We write  $\pi[i]$  to indicate the value of the element at position  $i$  (i.e.  $\pi_i$ ). For example, in the permutation  $\pi = 51342$ , The element 1 is at position 2 and the element at position 1 has value 5. Conveniently, we let  $\pi[i : j]$  stand for

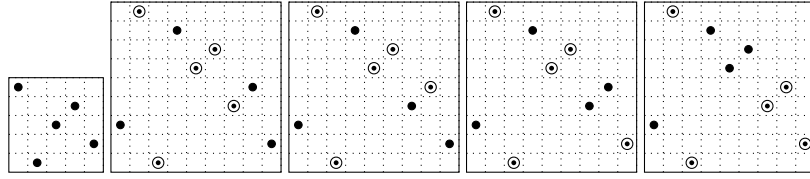


Fig. 1: The pattern  $\sigma = 51342$  and four occurrences of  $\sigma$  in  $391867452$ .

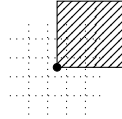


Fig. 2: The element is a RLMax if and only if the hashed area is empty.

$\pi_i \pi_{i+1} \dots \pi_j$ ,  $\pi[1 : j]$  stand for  $\pi[1 : j]$  and  $\pi[i : n]$  stand for  $\pi[i : n]$ .

It is convenient to use a geometric representation of permutations to ease the understanding of algorithms. The geometric representation corresponds to the set of points with coordinate  $(i, \pi[i])$  (see Figure 1).

When an element  $\pi[\alpha]$  is smaller (resp. larger) than an element  $\pi[\beta]$  by value (in the natural order of the set), we say that  $\pi[\alpha]$  is below (resp. above)  $\pi[\beta]$ , as a reference to the geometric representation of the permutation. Besides, the element with the largest value is called the topmost element and the element with the smallest value is called the bottommost element. For example, in the permutation  $\pi = 51342$ , 2 is below 4, the topmost element is 5 and the bottommost element is 1.

When an element  $\pi[\alpha]$  is smaller (resp. larger) than an element  $\pi[\beta]$  by position (in the order given by the permutation), we say that  $\pi[\alpha]$  is on the left of (resp. on the right of)  $\pi[\beta]$ . Besides, the element with the largest position is called the rightmost element and the element with the smallest position is called the leftmost element. For example, in the permutation  $\pi = 51342$ , 5 is on the left of 3, the leftmost element is 5 and the rightmost element is 2.

A permutation  $\sigma$  is said to *occur* in the permutation  $\pi$ , written  $\sigma \preceq \pi$ , if there exists a subsequence (not necessarily consecutive) elements of  $\pi$  that has the same relative order as  $\sigma$ . Such a subsequence is called an *occurrence* of  $\sigma$  in  $\pi$ . Otherwise,  $\pi$  is said to *avoid* the permutation  $\sigma$ . For example, the permutation  $\pi = 391867452$  has an occurrence of the pattern  $\sigma = 51342$ , as can be seen in the highlighted subsequence of  $\pi = 391867452$  (or  $\pi = 391867452$  or  $\pi = 391867452$  or  $\pi = 391867452$ ). Since the permutation  $\pi = 391867452$  contains no increasing subsequence of size four,  $\pi$  avoids 1234. For an occurrence  $s$  of  $\sigma$  in  $\pi$ , we say that  $\pi[j]$  correspond  $\sigma[i]$  in the occurrence or that  $\sigma[i]$  is matched to  $\pi[j]$  in the occurrence if and only if  $\pi[j] = s[i]$ . Geometrically,  $\pi$  has an occurrence of  $\sigma$  if there exists a set of points in  $\pi$  whose relative positions are the same as those of  $\sigma$  (see Figure 1). A *right-to-left maximum* (RLMax, for short) of  $\pi$  is an element that does not have any element above it and to its right (see Figure 2). Formally,  $\pi[i]$  is a RLMax if and only if  $\pi[i]$  is the topmost element of  $\pi[i : n]$ . Similarly  $\pi[i]$  is a *right-to-left minimum* (RLMin, for short) if and only if  $\pi[i]$  is the bottommost element of  $\pi[i : n]$ . A *bivincular permutation pattern*  $\tilde{\sigma}$  of size  $k$  is a permutation written in two-line notation (the top row is  $1 \overline{2} \dots \overline{k}$  and the bottom row is a permutation  $\sigma_1 \sigma_2 \dots \sigma_k$ ) with overlined elements in the top row and underlined elements in the bottom row. We have the following conditions on the top and bottom rows of

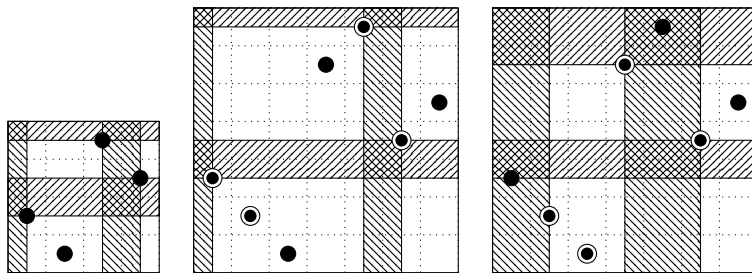


Fig. 3: From left to right, the bivincular pattern  $\tilde{\sigma} = \begin{smallmatrix} \overline{1234} \\ \perp 2143 \end{smallmatrix}$ , an occurrence of  $\tilde{\sigma}$  in 3216745, an occurrence of  $\sigma$  in 3216745 but not an occurrence of  $\tilde{\sigma}$  because the points (1, 3) and (5, 7) are in the forbidden areas.

$\sigma$ , as seen in [14] in Definition 1.4.1:

- If the bottom line of  $\tilde{\sigma}$  contains  $\sigma_i \sigma_{i+1} \dots \sigma_j$  then the elements corresponding to  $\sigma_i \sigma_{i+1} \dots \sigma_j$  in an occurrence of  $\sigma$  in  $\pi$  must be adjacent, whereas there is no adjacency condition for non-underlined consecutive elements. Moreover if the bottom row of  $\tilde{\sigma}$  begins with  $\perp \sigma_1$  then any occurrence of  $\tilde{\sigma}$  in a permutation  $\pi$  must begin with the leftmost element of  $\pi$ , and if the bottom row of  $\sigma$  ends with  $\sigma_k \perp$  then any occurrence of  $\tilde{\sigma}$  in a permutation  $\pi$  must end with the rightmost element of  $\pi$ .
- If the top line of  $\tilde{\sigma}$  contains  $\overline{i i + 1 \dots j}$  then the elements corresponding to  $i, i + 1, \dots, j$  in an occurrence of  $\sigma$  in  $\pi$  must be adjacent in values, whereas there is no value adjacency restriction for non-overlined elements. Moreover, if the top row of  $\tilde{\sigma}$  begins with  $\lceil 1$  then any occurrence of  $\tilde{\sigma}$  in a permutation  $\pi$  must contain the bottommost element of  $\pi$ , and if top row of  $\sigma$  ends with  $k \rceil$  then any occurrence of  $\tilde{\sigma}$  in a permutation  $\pi$  must contain the topmost element of  $\pi$ .

Given a bivincular permutation pattern  $\tilde{\sigma}$ ,  $\sigma$  refers to the bottom line of  $\tilde{\sigma}$  without any element underlined. For example, let  $\tilde{\sigma} = \begin{smallmatrix} \overline{1234} \\ \perp 2143 \end{smallmatrix}$ , in 3217845, **3217845** is an occurrence of  $\tilde{\sigma}$  but **3217845** is not and  $\sigma = 2143$ . The best general reference for bivincular pattern is [14].

Geometrically, we represent underlined and overlined elements by *forbidden areas*. If two elements are overlined then we draw a horizontal forbidden area between those two points. In an occurrence, we also draw the forbidden area between the matching of two overlined elements. This area must be empty to have a valid occurrence of the bivincular pattern. If the area is empty then there is no element between them when reading the permutation from bottom to top, in other words the matching elements are consecutive in value. If two elements are underlined then we draw a vertical forbidden area. (See Figure 3).

### 3 Both $\pi$ and $\sigma$ are wedge permutation

This section is devoted to present a fast algorithm for deciding if  $\sigma \preceq \pi$  in case both  $\pi$  and  $\sigma$  are wedge permutations. We begin with an easy and folk but crucial structure lemma.

**Lemma 1** *The first element of any wedge permutations must be either the bottommost or the topmost element.*

**Proof:** Any other initial element would serve as a ‘2’ in either a 231 or 213 with 1 and  $n$  as the ‘1’ and ‘3’ respectively.  $\square$

**Corollary 2**  $\pi$  is a wedge permutation of size  $n$  if and only if for  $1 \leq i \leq n$ ,  $\pi[i]$  is a RLMax or a RLMin.

As a consequence, a wedge permutation can be partitioned into three sets: the set of RLMax elements, the set of RLMin elements and the rightmost element which can be both a RLMax element and a RLMin element. The partition gives a bijection between the set of wedge permutations of size  $n$  with elements  $1, \dots, n$  and the set of binary words of size  $n - 1$ . The word  $w$  which corresponds to  $\pi$  is the word where each letter at position  $i$  represents whether  $\pi[i]$  is a RLMax element or a RLMin element. We call this bijection  $B$ . We also extend this transformation to subsequence of wedge permutations: Given a subsequence  $s$ , the binary word  $B(s)$  is the word where the letter at position  $i$  represents whether  $s[i]$  is a RLMax element or a RLMin element.

**Remark 3** The set of RLMax elements is a decreasing subsequence, indeed each element is on the left and above the next RLMax element by definition of a RLMax element. In the same fashion, the set of RLMin elements is an increasing subsequence. See Figure 4.

**Remark 4** We can draw a horizontal line (passing through the rightmost element) on a wedge permutations such that the upper half contains only a decreasing subsequence and the lower half contains only an increasing subsequence. This shape the permutation as a  $>$ , hence the name of wedge permutations. See Figure 4.

For any permutation, to figure out whether or not an element is a RLMax element or a RLMin element, one has to read the whole permutation from left to right starting from the position of the element. We give a corollary of Lemma 1, to guess it in constant time for a wedge permutation.

**Corollary 5** Let  $\pi$  be a wedge permutation and  $1 \leq i < n$ . Then,

1.  $\pi[i]$  is a RLMin element if and only if  $\pi[i] < \pi[i + 1]$ ;
2.  $\pi[i]$  is a RLMax element if and only if  $\pi[i] > \pi[i + 1]$ .

Now that we have highlighted some structural properties of wedge permutations, we can use this structure to solve the permutation pattern matching. More precisely, we use the bijection from wedge permutations to binary words to solve this problem, thanks to the following lemma.

**Lemma 6** Let  $\pi$  and  $\sigma$  be two wedge permutations. Then,  $\pi$  has an occurrence of  $\sigma$  if and only if there exists a subsequence  $t$  of  $\pi$  such  $B(t) = B(\sigma)$ .

**Proof:** The forward direction is obvious. We prove the backward direction by induction on the size of  $\sigma$ : if  $B(t) = B(\sigma)$  then  $t$  is an occurrence of  $\sigma$ . The base case is a pattern of size 2. Suppose that  $\sigma = 12$  and thus  $B(\sigma) = \text{RLMin}$ . Let  $t = \pi_{i_1} \pi_{i_2}$ ,  $i_1 < i_2$ , be a subsequence of  $\pi$  such that  $B(t) = \text{RLMin}$ , this reduces to saying that  $\pi_{i_1} < \pi_{i_2}$ , and hence that  $t$  is an occurrence of  $\sigma = 12$  in  $\pi$ . A similar argument shows that the lemma holds for  $\sigma = 21$ . Now, assume that the lemma is true for all patterns up to size  $k \geq 2$ . Let  $\sigma$  be a wedge permutation of size  $k + 1$  and let  $t$  be a subsequence of  $\pi$  of size  $k + 1$  such that  $B(t) = B(\sigma)$ . As  $B(t)[2:] = B(\sigma)[2:]$  by the induction hypothesis, it follows that  $t[2:]$  is an occurrence of  $\sigma[2:]$ . Moreover  $B(t)[1] = B(\sigma)[1]$  thus  $t[1]$  and  $\sigma[1]$  are both either the bottommost or the topmost element of their respective sequences. Therefore,  $t$  is an occurrence of  $\sigma$  in  $\pi$ . □

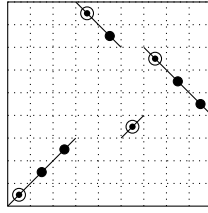


Fig. 4: The wedge permutation 123984765. Every line represents a factor, every circled point represents the leftmost element of each factor.

We are now ready to solve the permutation pattern matching problem in case both  $\pi$  and  $\sigma$  are wedge permutations.

**Proposition 7** *Let  $\pi$  and  $\sigma$  be two wedge permutations. One can decide whether  $\pi$  has an occurrence of  $\sigma$  in linear time.*

**Proof:** According to Lemma 6 the problem reduces to deciding whether  $B(\sigma)$  occurs as a subsequence in  $B(\pi)$ . This can be solved in linear time with a straightforward greedy approach as follows. We read both  $B(\sigma)$  and  $B(\pi)$  from left to right; when two letters are equal, we match them, and move to the next in both  $B(\sigma)$  and  $B(\pi)$  (if such letters exist); otherwise we stay at the same letter of  $B(\sigma)$  but move to the next one in  $B(\pi)$  (if it exists); we accept exactly when all letters of  $B(\sigma)$  have been matched.  $\square$

Thanks to Corollary 5, we do not need to compute the words  $B(\sigma)$  and  $B(\pi)$  before running the greedy algorithm. This computation can be done at the same time as running the algorithm, thus, giving an on-line algorithm.

## 4 Only $\sigma$ is a wedge permutation

This section focuses on the permutation pattern matching problem in case only the pattern  $\sigma$  is a wedge permutation. We need to consider a specific decomposition of  $\sigma$  into *factors*: we split the permutation into maximal sequences of consecutive RLMin and RLMax elements, respectively called a RLMin factor and a RLMax factor. This corresponds to splitting the permutation between every pair of RLMin – RLMax and RLMax – RLMin elements (see Figure 4). For the special case of a wedge permutation, this also corresponds to splitting the permutation into maximal sequences of elements consecutive in value. We label the factors from right to left. Note that the rightmost element can be both a RLMin or a RLMax, we take the convention that it is of the same type as the element before it for the factorization, so that the first factor (the rightmost factor) always contains at least two elements. For example,  $\sigma = 123984765$  is split as  $123 - 98 - 4 - 765$ . Hence  $\sigma = \text{factor}(4) \text{factor}(3) \text{factor}(2) \text{factor}(1)$  with  $\text{factor}(4) = 123$ ,  $\text{factor}(3) = 98$ ,  $\text{factor}(2) = 4$  and  $\text{factor}(1) = 765$ . See Figure 4.

**Remark 8** *A factor is either an increasing or a decreasing sequence of elements.*

To lighten a figure of an occurrence and to help the comprehension, we represent an occurrence in  $\pi$  (or a part of it) by a rectangle  $((A_x, A_y), (B_x, B_y))$  that contains at least all the points of the elements of the occurrence, where  $A$  is the bottom left corner and  $B$  is the top right corner. Formally the rectangle

$((A_x, A_y), (B_x, B_y))$  is the set of points in  $\pi[A_x : B_x]$  where each element is in  $[A_y, B_y]$ . Moreover we say that a rectangle is minimal if and only if it is the smallest rectangle that contains all of the elements of the occurrence. Consequently, the minimal rectangle of an occurrence is  $((lm, bm), (rm, tm))$  where  $lm$  stands for the position of the leftmost element,  $bm$  stands for the value of the bottommost element,  $rm$  stands for the position of the rightmost element and  $tm$  stands for the value of the topmost element. See Figure 5.

**Remark 9** *A rectangle contains an occurrence of a RLMin (resp. RLMax) factor if and only if the rectangle contains an increasing (resp. decreasing) subsequence of same size or larger than the size of the factor.*

We give a property of a wedge permutation that allows us to decide whether a rectangle contains an occurrence of the wedge permutation: given a rectangle we show that we can split the rectangle in two smaller rectangles. The splitting transforms the problem in deciding whether or not each of the two rectangles contains part of the wedge permutation. Intuitively, the problems on the two rectangles are easier than the problem on the original rectangle.

**Lemma 10** *There exists an occurrence of a wedge permutation starting with a leftmost RLmin (resp. RLmax) factor if and only if there exist two rectangles  $R_1$  and  $R_2$ , such that  $R_1$  is to the left and below (resp. to the left and above)  $R_2$ ,  $R_1$  contains an occurrence of the leftmost factor and  $R_2$  contains an occurrence of the rest.*

**Proof:** This is true as the leftmost factor is to the left and below (resp. to the left and above) the rest of the wedge permutation.  $\square$

We show how to compute the permutation pattern matching using this lemma. Note that the algorithm given in the proof is not the best we can do with respect to the time and space complexity, but it helps understanding the better version described in the proof of Proposition 15.

**Lemma 11** *Let  $\sigma$  be a wedge permutation of size  $k$  and  $\pi$  a permutation of size  $n$ . One can decide in polynomial time and space whether  $\pi$  contains an occurrence of  $\sigma$ .*

**Proof:** We introduce a set of values needed in computing the permutation pattern matching. Let  $LIS_\pi(((j, lb), (j', ub)))$  (resp.  $LDS_\pi(((j, lb), (j', ub)))$ ) be the size of the longest increasing (resp. decreasing) subsequence in  $((j, lb), (j', ub))$ . For all the rectangles  $LIS_\pi(((j, lb), (j', ub)))$  and  $LDS_\pi(((j, lb), (j', ub)))$  are computed in  $O(n^2 \log(\log(n)))$  time (see [4]).  $LIS_\pi(((j, lb), (j', ub)))$  (resp.  $LDS_\pi(((j, lb), (j', ub)))$ ) allows us to decide the existence of an occurrence of any LRMin (resp. LRMax) factor in the rectangle  $((j, lb), (j', ub))$  in constant time if we precomputed it for all the rectangles.

We solve the problem of deciding whether a rectangle  $((j, lb), (j', ub))$  contains an occurrence of factor  $(i) \dots$  factor  $(i')$ . More formally:

$$PM_\sigma^\pi(i, i', ((j, lb), (j', ub))) = \begin{cases} True & \text{if and only if } ((j, lb), (j', ub)) \text{ contains} \\ & \text{an occurrence of factor } (i) \dots \text{ factor } (i') \\ False & \text{Otherwise} \end{cases}$$

By definition  $\pi$  contains an occurrence of  $\sigma$  if and only if  $PM_\sigma^\pi(\ell, 1, ((1, 1), (n, n)))$  is true where  $\ell$  is the number of factors in  $\sigma$ . We show how to compute  $PM_\sigma^\pi(i, i', ((j, lb), (n, ub)))$  recursively.



- If the permutation is reduced to a factor then one has to decide if the rectangle contains an increasing or a decreasing factor with the same size or larger than the size of the unique factor. This case happens when  $i = i'$ :

- if  $factor(i)$  is a LRMin factor:

$$\begin{aligned} & \text{PM}_\sigma^\pi(i, i, ((j, lb), (n, ub))) = \\ & \begin{cases} True & \text{if } |factor(i)| \leq LIS_\pi(((j, lb), (n, ub))) \\ False & \text{Otherwise} \end{cases} \end{aligned}$$

- if  $factor(i)$  is a LRMax factor:

$$\begin{aligned} & \text{PM}_\sigma^\pi(i, i, ((j, lb), (n, ub))) = \\ & \begin{cases} True & \text{if } |factor(i)| \leq LDS_\pi(((j, lb), (n, ub))) \\ False & \text{Otherwise} \end{cases} \end{aligned}$$

- Otherwise, assuming that  $factor(i)$  is a LRMin (resp. LRMax) factor, we need to decide if there exists a splitting of  $((j, lb), (n, ub))$  into two rectangles  $R_1$  and  $R_2$  such that  $R_1$  is to the left and below (resp. above)  $R_2$ ,  $R_1$  contains an occurrence of  $factor(i)$  and  $R_2$  contains an occurrence of  $factor(i-1) \dots factor(i')$ . A direct strategy is to try every pair of rectangles where one rectangle is to the left and below (resp. above) the other and to decide whether the first one contains a occurrence of  $factor(i)$  and the second one contains an occurrence of  $factor(i-1) \dots factor(i')$ . Note that to reduce the number of pairs of rectangles to test, it is better to consider the biggest rectangles possible as long as the positions of the two rectangles are respected. Indeed if  $R'$  is contained in  $R$  and  $R'$  contains an occurrence then  $R$  also contains this occurrence, so we do not need to find an occurrence in both  $R$  and  $R'$  but only in  $R$ . Concretely we can always consider that  $R_1$  has for bottom left corner  $(j, lb)$  (resp. top right corner  $(j, ub)$ ) and that  $R_2$  has for top right corner  $(n, ub)$  (resp. bottom right corner  $(n, lb)$ ) and  $R_1$  is next to  $R_2$ . More formally:

- if  $factor(i)$  is a LRMin factor:

$$\begin{aligned} & \text{PM}_\sigma^\pi(i, i', ((j, lb), (n, ub))) = \\ & \bigvee_{\substack{j \leq j' < n \\ ub' < ub}} \text{PM}_\sigma^\pi(i, i, ((j, lb), (j', ub'))) \wedge \text{PM}_\sigma^\pi(i-1, i', ((j'+1, ub'+1), (n, ub))) \end{aligned}$$

- if  $factor(i)$  is a LRMax factor:

$$\begin{aligned} & \text{PM}_\sigma^\pi(i, i', ((j, lb), (n, ub))) = \\ & \bigvee_{\substack{j \leq j' < n \\ lb' > lb}} \text{PM}_\sigma^\pi(i, i, ((j, lb'), (j', ub))) \wedge \text{PM}_\sigma^\pi(i-1, i', ((j'+1, lb), (n, lb'-1))) \end{aligned}$$

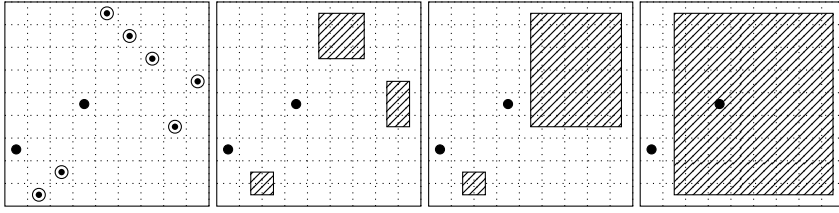


Fig. 5: From left to right, an occurrence of a permutation, the same occurrence where each occurrence of a factor is represented by the minimal rectangle, the same occurrence where the occurrence of the first two factors are represented by the minimal rectangle, and the same occurrence represented by its minimal rectangle.

□

Remark that given that the pattern starts with a RLMin (resp. RLMax), if the occurrence starts at the left edge of the rectangle (ie.  $\pi[j]$  is part of the occurrence), then as the leftmost element of the pattern is a RLMin (resp. RLMax) value, every element of the occurrence is above (resp. below) it, so  $\pi[j]$  can be used as lower (resp. upper) bound and thus as the bottom (resp. top) edge of the rectangle. In the algorithm, instead of finding any occurrence we find an occurrence starting at the left edge. This has two consequences: First we can remove one argument corresponding to the bottom (resp. top) edge as it can be easily computed and second, the condition of whether  $\sigma$  occurs in  $\pi$  is changed as we have to try every element of  $\pi$  as a starting element of an occurrence.

We extend our research to reduce the number of pairs of rectangles that we have to test. The idea is that when deciding whether a rectangle contains an occurrence of a pattern, to split the rectangle, the algorithm first "cuts" the rectangle vertically, so that we obtain two rectangles, the first one being on the left of the second one. Then the algorithm decides whether the second rectangle contains an occurrence of the "right part of the pattern". From all the occurrences that the algorithm could find, it is in our best interest to select the occurrence which is contained in the smallest rectangles possible, so that the first rectangle is bigger and thus it will contain more elements and so, will have a better chance to contain an occurrence of the left part of the pattern. Note that given that the leftmost factor of the pattern is a RLMin (resp. RLMax) factor, the left, right and top (resp. bottom) edges of the second rectangle is fixed. Indeed remember that in the algorithm, the second rectangle shares its top (resp. bottom) right corner with the original rectangle which gives the right and top (resp. bottom) edges and the algorithm has already "cut" the original rectangle vertically which gives the left edge. So the "smallest rectangle" can only be obtained using the bottom (resp. top) edge which should be the upmost (resp. bottommost) possible. The next lemma indicates which element is the topmost and the bottommost, and the next one and its corollary formalize what said above. But first we introduce another notation.

We introduce the notation  $\text{LMep}(s)$  (which stands for the leftmost element position): Suppose that  $s$  is a subsequence of  $S$ ,  $\text{LMep}(s)$  is the position of the leftmost element of  $s$  in  $S$ . Thus for every factor,  $\text{LMep}(\text{factor}(j))$  stands for the position in  $\sigma$  of the leftmost element of  $\text{factor}(j)$ . For the example preceding Remark 8,  $\text{LMep}(\text{factor}(4)) = 1$ ,  $\text{LMep}(\text{factor}(3)) = 4$ ,  $\text{LMep}(\text{factor}(2)) = 6$  and  $\text{LMep}(\text{factor}(1)) = 7$ .

**Lemma 12** *Given a wedge permutation  $\sigma$ , if  $\text{factor}(i)$  is a RLMin (resp. RLMax) factor the topmost (resp. bottommost) element of  $\text{factor}(i) \dots \text{factor}(1)$  is the leftmost element of  $\text{factor}(i - 1)$ .*

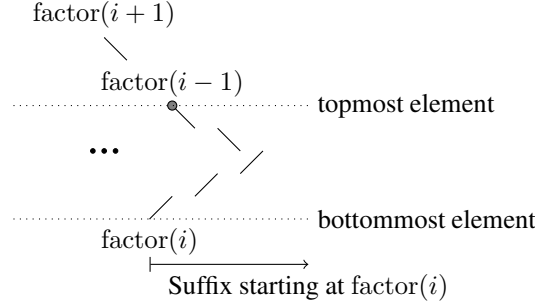


Fig. 6: The topmost element of the suffix starting at  $\text{factor}(i)$  is the leftmost element of  $\text{factor}(i-1)$  (represented by the grey dot).  $\text{PM}_\sigma^\pi(i, j)$  is the smallest value of the matching of the topmost element (the grey dot) in all the occurrences of the suffix starting at  $\text{LMep}(\text{factor}(i))$  in  $\pi[j : ]$ .

**Proof:** This lemma states that, given a wedge permutation if the permutation starts with a RLMIn (resp. RLMax) element then the topmost (resp. bottommost) element of this permutation is the first RLMax (resp. RLMIn) element (see Figure 6). This is easy to see from the shape of a wedge permutation. Formally, the RLMIn elements are below the RLMax elements, thus the topmost element must be the first RLMax element, which is the leftmost element of  $\text{factor}(i-1)$ . □

We also define  $S_\sigma^\pi(i, j)$  as the set of all subsequences  $s$  of  $\pi[j : ]$  that start at  $\pi[j]$  and that are occurrences of  $\text{factor}(i) \dots \text{factor}(1)$ .

**Lemma 13** *Let  $\sigma$  be a wedge permutation and  $\text{factor}(i)$  be a RLMIn (resp. RLMax) factor  $\sigma$ . Let  $\pi$  be a permutation and  $s$  a subsequence of  $\pi$  such that  $s \in S_\sigma^\pi(i, j)$  and  $s$  minimizes (resp. maximizes) the matching of the leftmost element of  $\text{factor}(i-1)$ . Let  $s'$  be a subsequence of  $\pi$  such that  $s' \in S_\sigma^\pi(i, j)$  and let  $t = t's'$  be a subsequence of  $\pi$  that extends  $s'$  on the right. Assume  $t$  is an occurrence of  $\text{factor}(i+1) \dots \text{factor}(1)$  such that the leftmost element of  $\text{factor}(i)$  is matched to  $\pi[j]$ . Then the subsequence  $t's$  is also an occurrence of  $\text{factor}(i+1) \dots \text{factor}(1)$  such that the leftmost element of  $\text{factor}(i)$  is matched to  $\pi[j]$ .*

Informally, this lemma states that we can replace the rectangle of an occurrence in  $S_\sigma^\pi(i, j)$  by another rectangle of an occurrence in  $S_\sigma^\pi(i, j)$  such that the second rectangle shares the same edges as the first one, except for the top edge which is lower. Especially the second rectangle can be chosen as the one with the lowest top edge in all the rectangles sharing the right, bottom and left edges. More formally, given any occurrence of  $\text{factor}(i+1) \text{factor}(i) \dots \text{factor}(1)$ , where  $\text{factor}(i)$  is a RLMIn (resp. RLMax) factor, we can replace the part of the occurrence where  $\text{factor}(i) \dots \text{factor}(1)$  occurs, by any occurrence that minimises (resp. maximises) the leftmost element of  $\text{factor}(i-1)$ . Indeed the leftmost element of  $\text{factor}(i-1)$  is the topmost (resp. bottommost) element of  $\text{factor}(i) \dots \text{factor}(1)$  (see Figure 6).

**Proof:** Let us consider the case where  $\text{factor}(i)$  is a RLMIn factor. By definition  $s$  is an occurrence of  $\sigma[\text{LMep}(\text{factor}(i)) : ]$ . First of all, remark that  $t'$  is an occurrence of  $\text{factor}(i+1)$ . So to prove that  $t's$  is an occurrence of  $\text{factor}(i+1) \dots \text{factor}(1)$  we need to prove that the elements of  $t'$  are above the elements of  $s$ . Since  $t's'$  is an occurrence of  $\text{factor}(i+1) \dots \text{factor}(1)$  it follows that the elements of  $t'$  are

above the elements of  $s'$ . Moreover the topmost element of  $s$  is below (or equal to) the topmost element of  $s'$  thus the elements of  $s$  are below the elements of  $t'$ . We use a symmetric argument if  $\text{factor}(i)$  is a RLM<sub>Max</sub> factor.

□

**Corollary 14** *Let  $\sigma$  be a wedge permutation,  $\text{factor}(i)$  be a RLM<sub>Min</sub> (resp. RLM<sub>Max</sub>) factor and  $s$  be a subsequence of  $\pi$  such that  $s \in S_{\sigma}^{\pi}(i, j)$  and that minimizes (resp. maximizes) the matching of the leftmost element of  $\text{factor}(i - 1)$ . The following statements are equivalent:*

- *There exists an occurrence of  $\sigma$  in  $\pi$  where the leftmost element of  $\text{factor}(i)$  is matched to  $\pi[j]$ .*
- *There exists an occurrence  $t$  of  $\text{factor}(\ell) \dots \text{factor}(i + 1)$  in  $\pi[: j - 1]$  such that  $ts$  is an occurrence of  $\sigma$  in  $\pi$  with the leftmost element of  $\text{factor}(i)$  matched to  $\pi[j]$ .*

**Proof:** The backward direction is trivial and the forward direction follows from Lemma 13.

□

This corollary takes a step further from the previous one, as it states that if there is no occurrence of  $\sigma$  in  $\pi$  where the leftmost element of  $\text{factor}(i)$  is matched to  $\pi[j]$  and such that the leftmost element of  $\text{factor}(i - 1)$  is minimized (resp. maximized) then there does not exist any occurrence at all.

**Proposition 15** *Let  $\sigma$  be a wedge permutation of size  $k$  and  $\pi$  a permutation of size  $n$ . One can decide in  $O(\max(kn^2, n^2 \log(\log(n))))$  time and  $O(n^3)$  space if  $\pi$  contains an occurrence of  $\sigma$ .*

**Proof:** The algorithm follows the previous one, it takes a rectangle and decide whether this rectangle contains an occurrence of  $\sigma$ , but instead of returning true or false, assuming that  $\text{factor}(i)$  is a RLM<sub>Min</sub> (resp. RLM<sub>Max</sub>) factor the algorithm return the optimal value of the top (resp. bottom) edge of a rectangle containing the pattern (or a special value that indicates that no occurrence exists). So that in the recursion the computed value of the right rectangle is used as the top (resp. bottom) edge of the left rectangle.

We first introduce a set of values needed in the problems. Let  $LIS_{\pi}(j, j', bound)$  (resp.  $LDS_{\pi}(j, j', bound)$ ) be the longest increasing (resp. decreasing) subsequence in  $\pi[j : j']$  starting at  $\pi[j]$ , with every element of this subsequence being smaller (resp. larger) or equal than  $bound$ .  $LIS_{\pi}$  and  $LDS_{\pi}$  can be computed in  $O(n^2 \log(\log(n)))$  time (see [4]).  $LIS_{\pi}(j, j', bound)$  (resp.  $LDS_{\pi}(j, j', bound)$ ) allows us to decide the existence of an occurrence starting at  $\pi[j]$  of any LRMin (resp. LRMax) factor in the rectangle  $((j, \pi[j]), (j', bound))$  (resp.  $((j, bound), (j', \pi[j]))$ ).

Given a RLM<sub>Min</sub> (resp. RLM<sub>Max</sub>) factor  $\text{factor}(i)$  of  $\sigma$  and a position  $j$  in  $\pi$ , we want the value of the top (resp. bottom) edge of any rectangle with bottom left (resp. with top left) corner  $(j, \pi[j])$  containing an occurrence of  $\text{factor}(i) \dots \text{factor}(1)$  starting at  $\pi[j]$  and which minimizes (resp. maximizes) its top (resp. bottom) edge or a value which indicates that no occurrence exists in this rectangle. More formally:

- If  $\text{factor}(i)$  is RLM<sub>Min</sub> factor.

$$PM_{\sigma}^{\pi}(i, j) =$$

$$\left\{ \begin{array}{l} \text{The top edge of any rectangle with bottom left corner } (j, \pi[j]) \\ \text{with right edge } n \text{ containing an occurrence of} \\ \text{factor}(i) \dots \text{factor}(1) \text{ starting at } \pi[j] \text{ which minimizes the top edge} \\ \text{Or } \infty \text{ if no occurrence exists} \end{array} \right.$$

- If  $\text{factor}(i)$  is RLMax factor.

$$\text{PM}_\sigma^\pi(i, j) = \left\{ \begin{array}{l} \text{The bottom edge of any rectangle with top left corner } (j, \pi[j]) \\ \text{with right edge } n \text{ containing an occurrence of} \\ \text{factor}(i) \dots \text{factor}(1) \text{ starting at } \pi[j] \text{ which maximizes its bottom edge} \\ \text{Or } 0 \text{ if no occurrence exists} \end{array} \right.$$

By definition, there exists an occurrence of  $\sigma$  in  $\pi$  if and only if there exists a  $j \in \{1, \dots, n\}$  such that  $\text{PM}_\sigma^\pi(\ell, j) \neq 0$  and  $\text{PM}_\sigma^\pi(\ell, j) \neq \infty$  with  $\ell$  the number of factors in  $\sigma$ .

We show how to compute recursively those values.

- If the permutation is reduced to a RLMin (resp. RLMax) factor then one has to compute the top (resp. bottom) edge of a rectangle that contains an increasing or a decreasing subsequence of the same size or larger than the size of the unique factor starting at  $\pi[j]$ . This case happens when  $i = 1$ :

- If  $\text{factor}(i)$  is a RLMin factor, then

$$\text{PM}_\sigma^\pi(1, j) = \min \{ \pi[j'] \mid |\text{factor}(1)| \leq \text{LIS}_\pi(j, j', \pi[j']) \}_{j' \geq j} \cup \{ \infty \}.$$

- If  $\text{factor}(i)$  is a RLMax factor, then

$$\text{PM}_\sigma^\pi(1, j) = \max \{ \pi[j'] \mid |\text{factor}(1)| \leq \text{LDS}_\pi(j, j', \pi[j']) \}_{j' \geq j} \cup \{ 0 \}.$$

- Otherwise, if  $\text{factor}(i)$  is a RLMin (resp. RLMax) factor, we split the rectangle into two rectangles  $R_1$  and  $R_2$  such that  $R_1$  is to the left and below (resp. to the left and above)  $R_2$ ,  $R_1$  contains an occurrence of  $\text{factor}(i)$  starting at  $j$  and  $R_2$  contains an occurrence of  $\text{factor}(i-1) \dots \text{factor}(1)$  starting at  $j' > j$ . As said before, we only need to test the pair of rectangles where the rectangle  $R_2$  has for left edge  $j'$  and has the highest bottom (resp. lowest top) edge containing an occurrence. So for  $R_2$  we want a rectangle starting at  $j'$  which contains an occurrence of  $\text{factor}(i-1) \dots \text{factor}(i')$  starting at  $j'$  with maximize the bottom (resp. minimize the top) edge. Moreover we also want to know the value of the bottom (resp. top) edge to use it as a bound for  $R_1$  so that that  $R_1$  is below  $R_2$ , in other words we want  $\text{PM}_\sigma^\pi(i-1, j')$ . As before  $R_1$  has to be biggest possible and to ensure that  $R_1$  is to the left and below (resp. to the left and above)  $R_2$ ,  $R_1$  must have for top right corner  $(j' - 1, \text{PM}_\sigma^\pi(i-1, j') - 1)$  (resp. bottom right corner  $(j' - 1, \text{PM}_\sigma^\pi(i-1, j') + 1)$ ). Finally in all the "correct" pairs of rectangles, we need the value of the top (resp. bottom) edge of a rectangle minimizing the top edge (resp. maximizing the bottom edge) containing the pair of rectangles. Note that the top (resp. bottom) edge has for value  $\pi[j']$  (the matching of  $\text{LMEp}(\text{factor}(i-1))$ ). Formally:

- If  $\text{factor}(i)$  is a RLMin factor:

$$\text{PM}_\sigma^\pi(i, j) = \min\{\infty\} \cup \{\pi[j'] \mid b = \text{PM}_\sigma^\pi(i-1, j') \text{ is not } 0 \text{ and } |\text{factor}(i)| \leq \text{LIS}_\pi(j, j'-1, b-1)\}_{j' < j}$$

- If  $\text{factor}(i)$  is a RLMax factor:

$$\text{PM}_\sigma^\pi(i, j) = \max\{0\} \cup \{\pi[j'] \mid b = \text{PM}_\sigma^\pi(i-1, j') \text{ is not } \infty \text{ and } |\text{factor}(i)| \leq \text{LDS}_\pi(j, j'-1, b+1)\}_{j' < j}$$

The number of factors is bounded by  $k$ . All instances of  $\text{LIS}_\pi$  and  $\text{LDS}_\pi$  can be computed in  $O(n^2 \log(\log(n)))$  time and this takes  $O(n^3)$  space (see [4]). There are  $n$  base cases that can be computed in  $O(n)$  time, thus computing every base case takes  $O(n^2)$  time. There are  $kn$  different instances of PM and each one of them takes  $O(n)$  time to compute, thus computing every instance of PM takes  $O(kn^2)$  time. Thus computing all the values takes  $O(\max(kn^2, n^2 \log(\log(n))))$  time. Every value takes  $O(1)$  space, thus the problem takes  $O(kn^2)$  space but  $\text{LIS}_\pi$  and  $\text{LDS}_\pi$  take  $O(n^3)$  space.  $\square$

## 5 Bivincular wedge permutation patterns

This section is devoted to the pattern matching problem with a bivincular wedge permutation pattern. Recall that a bivincular pattern generalizes a permutation pattern by being able to force elements in an occurrence to be consecutive in value or/and in position. Intuitively we cannot use the previous algorithm, as the restrictions on position and value are not managed.

Given a bivincular permutation pattern  $\tilde{\sigma}$ , we let  $\tilde{\sigma}[i : ]$  refer to the bivincular permutation pattern which has for top line the top line of  $\tilde{\sigma}$  where we remove the elements before  $i$  and has for bottom line the elements of  $\sigma[i : ]$  where  $m$  and  $m+1$  are underlined if and only if  $m$  and  $m+1$  are in  $\sigma[i : ]$ , and  $m$  and  $m+1$  are underlined in  $\tilde{\sigma}$ . For example given  $\tilde{\sigma} = \begin{smallmatrix} 12\overline{34} \\ \underline{2143} \end{smallmatrix}$ ,  $\sigma = 2143$  and  $\tilde{\sigma}[2 : ] = \begin{smallmatrix} \overline{234} \\ \underline{143} \end{smallmatrix}$ .

We describe other structure properties of wedge permutations needed to solve the problem.

**Lemma 16** *Let  $\sigma$  be a wedge permutation.*

- If  $\sigma[i]$  is a RLMin element and is not the rightmost element, then  $\sigma[i] + 1$  is to the right of  $\sigma[i]$ .
- If  $\sigma[i]$  is a RLMax element and is not the rightmost element, then  $\sigma[i] - 1$  is to the right of  $\sigma[i]$ .

**Proof:** For the first point, by contradiction,  $\sigma[i] + 1$  would serve as a ‘2’,  $\sigma[i]$  would serve as a ‘1’ and  $\sigma[i+1]$  would serve as a ‘3’ in an occurrence of 213. For the second point, by contradiction,  $\sigma[i] - 1$  would serve as a ‘2’,  $\sigma[i]$  would serve as a ‘3’ and  $\sigma[i+1]$  would serve as a ‘1’ in an occurrence of 231.  $\square$

**Lemma 17** *Let  $\sigma$  be a wedge permutation.*

- If  $m$  and  $m+1$  are both RLMin elements then any element between  $m$  and  $m+1$  (if any) is a RLMax element.

- If  $m$  and  $m - 1$  are both RLmax elements then any element between  $m$  and  $m - 1$  (if any) is a RLMin element.

**Proof:** For the first point, by contradiction, let  $\sigma[\alpha] = m$  and  $\sigma[\beta] = m + 1$  and suppose that there exists  $\alpha < \gamma < \beta$ , such that  $\sigma[\gamma]$  is a RLMin element. We know that RLMin are strictly increasing so  $\sigma[\alpha] < \sigma[\gamma] < \sigma[\beta]$ , which contradicts the fact that  $\sigma[\beta] = \sigma[\alpha] + 1$ .  $\square$

**Proposition 18** Let  $\tilde{\sigma}$  be a bivincular wedge permutation pattern of size  $k$  and  $\pi$  be a permutation of size  $n$ . One can decide in  $O(kn^4)$  time and  $O(kn^3)$  space if  $\pi$  contains an occurrence of  $\tilde{\sigma}$ .

**Proof:**

Consider the following problem: Given a lower bound lb, an upper bound ub, a position  $i$  of  $\sigma$  and a position  $j$  of  $\pi$ , we want to know if there exists an occurrence of  $\tilde{\sigma}[i : ]$  in  $\pi[j : ]$  with every element of the occurrence in  $[lb, ub]$  and starting at  $\pi[j]$ . In other words, we want to know if the rectangle with bottom left corner  $(j, lb)$  and with top right corner  $(n, ub)$  contains an occurrence of  $\tilde{\sigma}[i : ]$  starting at  $\pi[j]$ . More formally:

$$\text{PM}_{\pi}^{\tilde{\sigma}}(lb, ub, i, j) = \begin{cases} \text{true} & \text{if } \pi[j : ] \text{ has an occurrence of the bivincular pattern } \tilde{\sigma}[i : ] \\ & \text{with every element of the occurrence in } [lb, ub] \\ & \text{and starting at } \pi[j] \\ & \text{and if } \overline{\sigma[i](\sigma[i] + 1)} \text{ or } \sigma[i]^{\lceil} \text{ appear in } \tilde{\sigma} \text{ then } \pi[j] = ub \\ & \text{and if } \overline{(\sigma[i] - 1)\sigma[i]} \text{ or } \lceil \sigma[i] \text{ appear in } \tilde{\sigma} \text{ then } \pi[j] = lb \\ \text{false} & \text{otherwise} \end{cases}$$

Clearly if  $\lceil \sigma[1]$  does not appear in  $\tilde{\sigma}$  then  $\pi$  contains an occurrence of  $\tilde{\sigma}$  if and only if  $\bigcup_{0 < j} \text{PM}_{\pi}^{\tilde{\sigma}}(1, n, 1, j)$  is true. If  $\lceil \sigma[1]$  appear in  $\sigma$  then  $\pi$  contains an occurrence of the bivincular wedge permutation pattern  $\tilde{\sigma}$  if and only if  $\text{PM}_{\pi}^{\tilde{\sigma}}(1, n, 1, 1)$  is true.

We show how to compute recursively those values. Informally, to find an occurrence of  $\tilde{\sigma}[i : ]$  in  $\pi[j : ]$ , given that  $\sigma[i]$  is a RLMin element, we need to find a rectangle  $R$  in  $\pi$  such that  $R$  contains an occurrence of  $\tilde{\sigma}[i + 1 : ]$  and  $R$  is to the right and above  $\pi[j]$ . Moreover

- If  $\overline{\sigma[i]\sigma[i + 1]}$  then we require that  $\pi[j]$  and  $R$  are next to each other horizontally and that the occurrence in  $R$  starts at the left edge of  $R$ . In other words  $R$  has for left edge  $j + 1$ .
- If  $\overline{\sigma[i](\sigma[i] + 1)}$  then we require that  $\pi[j]$  and  $R$  are next to each other vertically and that the minimal element in the occurrence is on the bottom edge of  $R$ . In other words  $R$  has for bottom edge  $\pi[j] + 1$ .

Note that the parameters lb, ub and  $j$  corresponding to the occurrence of  $\tilde{\sigma}[i + 1 : ]$  are respectively, the bottom edge, the top edge and the left edge of the rectangle  $R$ . The case where  $\sigma[i]$  is a RLMax element can be dealt with symmetrically. More formally:

**BASE:**

$$PM_{\pi}^{\tilde{\sigma}}(\text{lb}, \text{ub}, k, j) = \begin{cases} \text{true} & \text{if } \pi[j] \in [\text{lb}, \text{ub}] \\ & \text{and if } \sigma[k]_{\downarrow} \text{ appears in } \tilde{\sigma} \text{ then } j = n \\ & \text{and if } \sigma[k]_{\leftarrow} \text{ appears in } \tilde{\sigma} \text{ then } j = 1 \\ & \text{and if } \sigma[k]_{\uparrow} \text{ appears in } \tilde{\sigma} \text{ then } \pi[j] = \text{ub} = n \\ & \text{and if } \sigma[k]_{\uparrow} \text{ appears in } \tilde{\sigma} \text{ then } \pi[j] = \text{lb} = 1 \\ & \text{and if } \overline{(\sigma[k] - 1)\sigma[k]} \text{ appears in } \tilde{\sigma} \text{ then } \pi[j] = \text{lb} \\ & \text{and if } \overline{(\sigma[k]\sigma[k] + 1)} \text{ appears in } \tilde{\sigma} \text{ then } \pi[j] = \text{ub} \\ \text{false} & \text{otherwise} \end{cases}$$

The base case finds an occurrence for the rightmost element of the pattern. If the rightmost element does not have any restriction on positions and on values, then  $PM_{\pi}^{\tilde{\sigma}}(\text{lb}, \text{ub}, k, j)$  is true if and only if  $\sigma[k]$  is matched to  $\pi[j]$ . This is true if  $\pi[j] \in [\text{lb}, \text{ub}]$ . If  $\sigma[k]_{\downarrow}$  appears in  $\tilde{\sigma}$  then  $\sigma[k]$  must be matched to the rightmost element of  $\pi$  thus  $j$  must be  $n$ . If  $\sigma[k]_{\leftarrow}$  appears in  $\tilde{\sigma}$  then  $\sigma[k]$  must be matched to the leftmost element thus  $j$  must be 1. If  $\sigma[k]_{\uparrow}$  appears in  $\tilde{\sigma}$  then  $\sigma[k]$  must be matched to the topmost element which is  $n$ . If  $\sigma[k]_{\uparrow}$  appears in  $\tilde{\sigma}$  then  $\sigma[k]$  must be matched to the bottommost element which is 1. If  $\overline{(\sigma[k] - 1)\sigma[k]}$  appears in  $\tilde{\sigma}$  then the matching elements of  $\sigma[k]$  and  $\sigma[k] - 1$  must be consecutive in value, by recursion the value of the element matching  $\sigma[k] - 1$  plus 1 will be recorded in lb, thus  $\sigma[k]$  must be matched to lb. If  $\overline{(\sigma[k]\sigma[k] + 1)}$  appears in  $\tilde{\sigma}$  then the element matching  $\sigma[k]$  and  $\sigma[k] + 1$  must be consecutive in value, by recursion the value of the element matching  $\sigma[k] + 1$  minus 1 will be recorded in ub, thus  $\sigma[k]$  must be matched to ub.

**STEP:**

We consider 3 cases for the problem  $PM_{\pi}^{\tilde{\sigma}}(\text{lb}, \text{ub}, i, j)$ :

- If  $\pi[j] \notin [\text{lb}, \text{ub}]$  then:

$$PM_{\pi}^{\tilde{\sigma}}(\text{lb}, \text{ub}, i, j) = \text{false}$$

which is immediate from the definition.

- If  $\pi[j] \in [\text{lb}, \text{ub}]$  and  $\sigma[i]$  is a RLMin element then:

$$PM_{\pi}^{\tilde{\sigma}}(\text{lb}, \text{ub}, i, j) =$$



$$\left\{ \begin{array}{l}
\bigvee_{\ell > j} \text{PM}_{\pi}^{\tilde{\sigma}}(\pi[j] + 1, \text{ub}, i + 1, \ell) \quad \text{if } \sigma[i] \text{ is not underlined} \\
\hspace{10em} \text{and } \sigma[i] \text{ is not overlined} \\
\bigvee_{\ell > j} \text{PM}_{\pi}^{\tilde{\sigma}}(\pi[j] + 1, \text{ub}, i + 1, \ell) \quad \text{if } \sigma[i] \text{ is not underlined} \\
\hspace{10em} \text{and } \overline{(\sigma[i] - 1)\sigma[i]} \text{ or } \ulcorner \sigma[i] \\
\hspace{10em} \text{appears in } \tilde{\sigma} \\
\hspace{10em} \text{and } \pi[j] = \text{lb} \\
\text{PM}_{\pi}^{\tilde{\sigma}}(\pi[j] + 1, \text{ub}, i + 1, j + 1) \quad \text{if } \underline{\sigma[i]\sigma[i + 1]} \\
\hspace{10em} \text{appears in } \tilde{\sigma} \\
\hspace{10em} \text{and } \sigma[i] \text{ is not overlined} \\
\text{PM}_{\pi}^{\tilde{\sigma}}(\pi[j] + 1, \text{ub}, i + 1, j + 1) \quad \text{if } \underline{\sigma[i]\sigma[i + 1]} \\
\hspace{10em} \text{and } \overline{(\sigma[i] - 1)\sigma[i]} \text{ or } \ulcorner \sigma[i] \\
\hspace{10em} \text{appear in } \tilde{\sigma} \\
\hspace{10em} \text{and } \pi[j] = \text{lb} \\
\text{false} \hspace{10em} \text{otherwise}
\end{array} \right.$$

Remark that  $\sigma[i]$  can be matched to  $\pi[j]$  because  $\pi[j] \in [\text{lb}, \text{ub}]$ . Thus if  $\pi[j+1 : ]$  has an occurrence of  $\tilde{\sigma}[i + 1 : ]$  with every element of the occurrence in  $[\pi[j] + 1, \text{ub}]$  and if the condition on position between  $\sigma[i]$  and  $\sigma[i+1]$  (if any) is respected and the condition on value between  $\sigma[i]$  and  $\sigma[i+1]$  (if any) is respected then  $\pi[j : ]$  has an occurrence of  $\tilde{\sigma}[i : ]$ . To decide the latter condition, by recursion it is enough to know if there exists  $\ell, j < \ell$  such that  $\text{PM}_{\pi}^{\tilde{\sigma}}(\pi[j] + 1, \text{ub}, i + 1, \ell)$  is true. The first case corresponds to an occurrence without restriction on position and on value, it is enough to know if there exists  $\ell > j$  such that  $\text{PM}_{\pi}^{\tilde{\sigma}}(\pi[j] + 1, \text{ub}, i + 1, \ell)$  is true. The second case asks for the matching of  $\sigma[i] - 1$  and  $\sigma[i]$  to be consecutive in value, but the matching of  $\sigma[i] - 1$  is  $\text{lb} - 1$  thus we want  $\pi[j] = \text{lb}$ . The third case asks for the matching of  $\sigma[i]$  and  $\sigma[i + 1]$  to be consecutive in positions, thus the matching of  $\sigma[i + 1]$  must be  $\pi[j + 1]$ . The fourth case is a union of the second and third case.

- If  $\pi[j] \in [\text{lb}, \text{ub}]$  and  $\sigma[i]$  is a RLMax element then:

$$\text{PM}_{\pi}^{\tilde{\sigma}}(\text{lb}, \text{ub}, i, j) =$$

$$\left\{ \begin{array}{ll}
\bigvee_{\ell > j} \text{PM}_{\pi}^{\tilde{\sigma}}(\text{lb}, \pi[j] - 1, i + 1, \ell) & \text{if } \sigma[i] \text{ is not underlined} \\
& \text{and } \sigma[i] \text{ is not overlined} \\
\bigvee_{\ell > j} \text{PM}_{\pi}^{\tilde{\sigma}}(\text{lb}, \pi[j] - 1, i + 1, \ell) & \text{if } \sigma[i] \text{ is not underlined} \\
& \text{and } \overline{\sigma[i](\sigma[i] + 1)} \text{ or } \sigma[i]^{\uparrow} \\
& \text{appear in } \tilde{\sigma} \\
& \text{and } \pi[j] = \text{ub} \\
\text{PM}_{\pi}^{\tilde{\sigma}}(\text{lb}, \pi[j] - 1, i + 1, j + 1) & \text{if } \underline{\sigma[i]\sigma[i + 1]} \\
& \text{appears in } \tilde{\sigma} \\
& \text{and } \sigma[i] \text{ is not overlined} \\
\text{PM}_{\pi}^{\tilde{\sigma}}(\text{lb}, \pi[j] - 1, i + 1, j + 1) & \text{if } \underline{\underline{\sigma[i]\sigma[i + 1]}} \\
& \text{and } \overline{\sigma[i](\sigma[i] + 1)} \text{ or } \sigma[i]^{\uparrow} \\
& \text{appear in } \tilde{\sigma} \\
& \text{and } \pi[j] = \text{ub} \\
\text{false} & \text{otherwise}
\end{array} \right.$$

The same remark as in the previous case holds.

Remark that there are constraints that do not appear when we compute  $\text{PM}_{\pi}^{\tilde{\sigma}}(*, *, i, *)$ . Especially in the case where  $\sigma[i]$  is a RLMin in the conditions of  $\underline{\sigma[i - 1]\sigma[i]}$  or/and  $\overline{\sigma[i](\sigma[i] + 1)}$  are not considered in the recursion.  $\underline{\sigma[i - 1]\sigma[i]}$  is not considered because it is up to  $\text{PM}_{\pi}^{\tilde{\sigma}}(*, *, i - 1, *)$  to ensure that the elements corresponding to elements at position  $i - 1$  and  $i$  in an occurrence are next to each other in position.  $\overline{\sigma[i](\sigma[i] + 1)}$  is not considered because  $\sigma[i] + 1$  is on the right of  $\sigma[i]$  (see Lemma 16) and thus will be taken care during the calls of  $\text{PM}_{\pi}^{\tilde{\sigma}}(*, *, i', *)$  for some  $i' > i$ . In the same fashion, when  $\sigma[i]$  is a RLMax  $\underline{\sigma[i - 1]\sigma[i]}$  does not appear in the conditions for the exact same reason and  $\overline{(\sigma[i] - 1)\sigma[i]}$  because  $\sigma[i] - 1$  is on the right of  $\sigma[i]$ .

Clearly the procedure returns true if  $\pi$  contains an occurrence of  $\tilde{\sigma}$  if there is no constraint on position and on value. We now discuss how the position and value constraints are taken into account so that the algorithm returns true if and only if  $\pi$  has an occurrence of  $\tilde{\sigma}$ .

**Position Constraint.** There are 3 types of position constraints that can be added by underlined elements.

- If  $\lfloor \sigma[1]$  appears in  $\tilde{\sigma}$  then the leftmost element of  $\sigma$  must be matched to the leftmost element of  $\pi$  ( $\sigma[1]$  is matched to  $\pi[1]$  in an occurrence of  $\tilde{\sigma}$  in  $\pi$ ). This constraint is satisfied by requiring that the occurrence starts at the leftmost element of  $\pi$ : if  $\text{PM}_{\pi}^{\tilde{\sigma}}(1, n, 1, 1)$  is true.
- If  $\sigma[k] \rfloor$  appears in  $\tilde{\sigma}$  then the rightmost element  $\sigma$  must be matched the rightmost element of  $\pi$  ( $\sigma[k]$  is matched to  $\pi[n]$  in a occurrence of  $\tilde{\sigma}$  in  $\pi$ ). This constraint is checked in the base case.
- If  $\underline{\sigma[i]\sigma[i + 1]}$  appears in  $\tilde{\sigma}$  then the positions of the element matching  $\sigma[i]$  and  $\sigma[i + 1]$  must be consecutive. In other words, if  $\sigma[i]$  is matched to  $\pi[j]$  then  $\sigma[i + 1]$  must be matched to  $\pi[j + 1]$ . We ensure this restriction by recursion by requiring that the matching of  $\sigma[i + 1 : ]$  starts at position  $j + 1$ .

**Value Constraint.** There are 3 types of value constraints that can be added by overlined elements.

- If  $\overline{\sigma[i]}$  appears in  $\tilde{\sigma}$  (and thus  $\sigma[i] = 1$ ) then the bottommost element of  $\sigma$  must be matched to the bottommost element of  $\pi$ .
  - If  $\sigma[i]$  is a RLMin element, then remark that:
    - \* Every problem  $\text{PM}_{\pi}^{\tilde{\sigma}}(\text{lb}, *, i, *)$  is true only if  $\sigma[i]$  is matched to the element with value lb (by recursion). So it is enough to require that  $\text{lb} = 1$ .
    - \* The recursive calls for  $\sigma[1], \dots, \sigma[i-1]$  do not change the lower bound as  $\sigma[i]$  is the leftmost RLMin element, indeed the element 1 is the leftmost RLMin for any permutation. Finally the recursive calls for RLMax elements do not change the lower bound.
    - \* The first call of the problem has for parameter  $\text{lb} = 1$ .
 So  $\text{PM}_{\pi}^{\tilde{\sigma}}(*, *, i, *)$  return true only if  $\sigma[i]$  is matched to 1.
  - If  $\sigma[i]$  is a RLMax element then  $i = k$  ( $\sigma[i]$  is the rightmost element). Thus every  $\text{PM}_{\pi}^{\tilde{\sigma}}(*, *, i, *)$  is a base case and is true only if  $\sigma[i]$  is matched to lb. Moreover recursive calls for RLMax elements do not change the lower bound. So  $\text{PM}_{\pi}^{\tilde{\sigma}}(*, *, i, *)$  return true only if  $\sigma[i]$  is matched to  $\text{lb} = 1$ .
- If  $\overline{\sigma[i]^\top}$  appears in  $\tilde{\sigma}$  (and thus  $\sigma[i] = k$ ) then the topmost element of  $\sigma$  must be matched to the topmost element of  $\pi$ .
  - If  $\sigma[i]$  is a RLMax element, then remark that:
    - \* Every problem  $\text{PM}_{\pi}^{\tilde{\sigma}}(*, \text{ub}, i, *)$  is true only if  $\sigma[i]$  is matched to the element with value ub (by recursion). So it is enough to require that  $\text{ub} = n$ .
    - \* The recursive calls for  $\sigma[1], \dots, \sigma[i-1]$  do not change the upper bound as  $\sigma[i]$  is the leftmost RLMax element, indeed the element  $k$  is the leftmost RLMax for any permutation. Finally the recursive calls for RLMin elements do not change the upper bound.
    - \* The first call of the problem has for parameter  $\text{ub} = n$ .
 So  $\text{PM}_{\pi}^{\tilde{\sigma}}(*, *, i, *)$  return true only if  $\sigma[i]$  is matched to  $n$ .
  - If  $\sigma[i]$  is a RLMin element then  $i = k$  ( $\sigma[i]$  is the rightmost element). Thus every  $\text{PM}_{\pi}^{\tilde{\sigma}}(*, *, i, *)$  is a base case and is true if  $\sigma[i]$  is matched to ub. Moreover recursive calls for RLMin elements do not change the upper bound. So  $\text{PM}_{\pi}^{\tilde{\sigma}}(*, *, i, *)$  return true only if  $\sigma[i]$  is matched to  $\text{ub} = n$ .
- If  $\overline{\sigma[i]\sigma[i']}$  appears in  $\tilde{\sigma}$ , (which implies that  $\sigma[i'] = \sigma[i] + 1$ ) and  $i < i'$  (the case where  $i > i'$  can be dealt with symmetry) so  $\sigma[i]$  is matched to  $\pi[j]$  and  $\sigma[i']$  is matched to  $\pi[j] + 1$ .
  - The case where  $\sigma[i]$  is a RLMax element is impossible, since  $\sigma[i']$  is to the right and above  $\sigma[i]$
  - If  $\sigma[i]$  is a RLMin element,  $\sigma[i']$  is a RLMax element, then remark that
    - \*  $i' = k$ , indeed if  $\sigma[i']$  is not the rightmost element, there would exist an element between  $\sigma[i]$  and  $\sigma[i']$ . So every recursive call  $\text{PM}_{\pi}^{\tilde{\sigma}}(\text{lb}, *, i', *)$  is solved as a base case. So  $\text{PM}_{\pi}^{\tilde{\sigma}}(\text{lb}, *, i', *)$  is true only if  $\sigma[i']$  is matched to the element lb.

- \* The recursive calls for  $\sigma[i+1], \dots, \sigma[i'-1]$  do not change the lower bound. Indeed  $\sigma[i]$  is the rightmost RLMin. So  $\sigma[i+1], \sigma[i+2], \dots, \sigma[i'-1]$  are RLMax elements. Moreover recursive calls for a RLMax do not change the lower bound.
- \*  $\text{PM}_{\pi}^{\tilde{\sigma}}(\text{lb}, *, i, *)$  sets the lb to  $\pi[j] + 1$  and matches  $\sigma[i]$  to  $\pi[j]$ .

So  $\sigma[i]$  is matched to  $\pi[j]$  and  $\sigma[i']$  is matched to  $\pi[j] + 1$ .

- If  $\sigma[i]$  is a RLMin element and  $\sigma[i']$  is a RLMin element then first remark:
  - \* Every recursive call  $\text{PM}_{\pi}^{\tilde{\sigma}}(\text{lb}, *, i', *)$  is true only if  $\sigma[i']$  is matched to the element with value lb.
  - \* The recursive calls for  $\sigma[i+1], \dots, \sigma[i'-1]$  do not change the lower bound. Indeed from Lemma 17,  $\sigma[i+1], \dots, \sigma[i'-1]$  are RLMax elements. Finally the recursive calls for RLMax elements do not change the lower bound.
  - \*  $\text{PM}_{\pi}^{\tilde{\sigma}}(*, *, i, *)$  sets lb to  $\pi[j] + 1$  and matches  $\sigma[i]$  to  $\pi[j]$ .

So  $\sigma[i]$  is matched to  $\pi[j]$  and  $\sigma[i']$  is matched to  $\pi[j] + 1$ .

There are  $n^3$  base cases that can be computed in constant time and there are  $kn^3$  different cases. Each case takes up to  $O(n)$  time to compute. Thus computing all the cases take  $O(kn^4)$  time. Each case take  $O(1)$  space, thus we need  $O(kn^3)$  space. □

## 6 Computing the longest wedge permutation pattern

This section is focused on a problem related to the permutation pattern matching problem. This continues the work done in [6] and in [16].

Given a set of permutations, one must compute the longest permutation which occurs in each permutation of the set. This problem is known to be NP-Hard for an arbitrary size of the set even when all the permutations of this set are separable permutations (see [6]). We show how to compute the longest wedge permutation occurring in a set. We do not hope that this problem is solvable in polynomial time if the size of the set is not fixed. Indeed the size of the set appears in the exponent in the complexity of the algorithm. Thus we focus on the cases where only one or two permutations are given in set.

Conveniently, we say that a subsequence is a wedge subsequence if and only if the permutation represented by the subsequence is a wedge permutation.

We start with the easiest case where we are given just one input permutation. We need the set of RLMax elements and the set of RLMin elements.  $A(\pi) = \{i | \pi[i] \text{ is a RLMin element}\} \cup \{n\}$  and  $D(\pi) = \{i | \pi[i] \text{ is a RLMax element}\} \cup \{n\}$ .

**Proposition 19** *If  $s_i$  is the longest increasing subsequence with last element at position  $f$  in  $\pi$  and  $s_d$  is the longest decreasing subsequence with last element at position  $f$  in  $\pi$  then  $s_i \cup s_d$  is a longest wedge subsequence with last element at position  $f$  in  $\pi$ .*

**Proof:** Let us first prove that we have a wedge subsequence.  $s_i$  is an increasing subsequence with values below or equal  $\pi[f]$  and  $s_d$  is a decreasing subsequence with values above or equal  $\pi[f]$ , so  $s_i \cup s_d$  is a wedge subsequence. Let us prove that this is a longest. Let  $s$  be a wedge subsequence with its rightmost

element at position  $f$  in  $\pi$  such that  $|s| > |s_i \cup s_d|$ , first note that  $A(s)$  is also an increasing subsequence with its rightmost element at position  $f$  in  $\pi$  and  $D(s)$  is also a decreasing subsequence with its rightmost element at position  $f$  in  $\pi$ , as  $|s| > |s_i \cup s_d|$  then either  $|A(s)| > |s_i|$  or  $|D(s)| > |s_d|$ , which is in contradiction with the definition of  $s_i$  and  $s_d$ .  $\square$

**Proposition 20** *Let  $\pi$  be a permutation. One can compute the longest wedge subsequence that can occur in  $\pi$  in  $O(n \log(\log(n)))$  time and in  $O(n)$  space.*

**Proof:** Proposition 19 leads to an algorithm where one computes the longest increasing and decreasing subsequence ending at every possible position and then finds the maximum sum of longest increasing and decreasing subsequence ending at the same position. Computing the longest increasing subsequences and the longest decreasing subsequences can be done in  $O(n \log(\log(n)))$  time and  $O(n)$  space (see [4]), then finding the maximum can be done in linear time.  $\square$

We now consider the case where the input is composed of two permutations.

**Proposition 21** *Given two permutations  $\pi_1$  of size  $n_1$  and  $\pi_2$  of size  $n_2$ , one can compute the longest common wedge subsequence in  $O(n_1^3 n_2^3)$  time and space.*

**Proof:** Consider the following problem that computes the longest wedge subsequence common to  $\pi_1$  and  $\pi_2$ : Given two permutations  $\pi_1$  and  $\pi_2$ , we define  $\text{LCS}_{\pi_1, \text{lb}_1, \text{ub}_1}^{\pi_2, \text{lb}_2, \text{ub}_2}(i_1, i_2)$

$$= \max \{ |s| \mid s \text{ occurs } \pi_1[i_1 :] \text{ with every element of the occurrence in } [\text{lb}_1, \text{ub}_1] \text{ and } s \text{ occurs } \pi_2[i_2 :] \text{ with every element of the occurrence in } [\text{lb}_2, \text{ub}_2] \text{ and } s \text{ is a wedge subsequence} \}$$

We show how to solve this problem by dynamic programming.

**BASE:**

$$\text{LCS}_{\pi_1, \text{lb}_1, \text{ub}_1}^{\pi_2, \text{lb}_2, \text{ub}_2}(n_1, n_2) = \begin{cases} 1 & \text{if } \text{lb}_1 \leq \pi_1[n_1] \leq \text{ub}_1 \text{ and } \text{lb}_2 \leq \pi_2[n_2] \leq \text{ub}_2 \\ 0 & \text{otherwise} \end{cases}$$

**STEP:**

$$\text{LCS}_{\pi_1, \text{lb}_1, \text{ub}_1}^{\pi_2, \text{lb}_2, \text{ub}_2}(i_1, i_2) = \max \begin{cases} \text{LCS}_{\pi_1, \text{lb}_1, \text{ub}_1}^{\pi_2, \text{lb}_2, \text{ub}_2}(i_1, i_2 + 1) \\ \text{LCS}_{\pi_1, \text{lb}_1, \text{ub}_1}^{\pi_2, \text{lb}_2, \text{ub}_2}(i_1 + 1, i_2) \\ M_{\pi_1, \text{lb}_1, \text{ub}_1}^{\pi_2, \text{lb}_2, \text{ub}_2}(i_1, i_2) \end{cases}$$

with

$$M_{\pi_1, \text{lb}_1, \text{ub}_1}^{\pi_2, \text{lb}_2, \text{ub}_2}(i_1, i_2) = \begin{cases} 1 + \text{LCS}_{\pi_1, \pi_1[i_1]+1, \text{ub}_1}^{\pi_2, \pi_2[i_2]+1, \text{ub}_2}(i_1 + 1, i_2 + 1) & \pi_1[i_1] < \text{lb}_1 \\ & \text{and } \pi_2[i_2] < \text{lb}_2 \\ 1 + \text{LCS}_{\pi_1, \text{lb}_1, \pi_1[i_1]-1}^{\pi_2, \text{lb}_2, \pi_2[i_2]-1}(i_1 + 1, i_2 + 1) & \pi_1[i_1] > \text{ub}_1 \\ & \text{and } \pi_2[i_2] > \text{ub}_2 \\ 0 & \text{otherwise} \end{cases}$$

The solution to the problem relies on the fact that the longest wedge subsequence is found either by considering the problem with  $\pi_1[i_1 : ]$  and  $\pi_2[i_2 + 1 : ]$  or by considering the problem with  $\pi_1[i_1 + 1 : ]$  and  $\pi_2[i_2 : ]$  or by matching  $\pi_1[i_1]$  and  $\pi_2[i_2]$  and adding to the solution the LCS for  $\pi_1[i_1 + 1 : ]$  and  $\pi_2[i_2 + 1 : ]$  which is compatible, meaning that if we consider the current elements to correspond to a RLMin (resp. RLMax) element in the longest wedge subsequence then we consider only the solution with elements above (below)  $\pi_1[i_1]$  for the occurrence in  $\pi_1[i_1 + 1 : ]$  and  $\pi_2[i_2]$  for the occurrence in  $\pi_2[i_2 + 1 : ]$ .

These relations lead to a  $O(|\pi_1|^3|\pi_2|^3)$  time and  $O(|\pi_1|^3|\pi_2|^3)$  space algorithm. Indeed there are  $|\pi_1|^3|\pi_2|^3$  possible cases for the problem and each case is solved in constant time.  $\square$

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