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Box-ball systems and RSK tableaux

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Abstract. A box-ball system is a collection of discrete time states. At each state, we have a collection of countably many boxes with each integer from 1 to n assigned to a unique box; the remaining boxes are considered empty. A permutation on n objects gives a box-ball system state by assigning the permutation in one-line notation to the first n boxes. After a finite number of steps, the system will reach a so-called soliton decomposition which has an integer partition shape. We prove the following: if the soliton decomposition of a permutation is a standard Young tableau or if its shape coincides with its Robinson–Schensted (RS) partition, then its soliton decomposition and its RS insertion tableau are equal. We study the time required for a box-ball system to reach a steady state. We also generalize Fukuda's single-carrier algorithm to algorithms with more than one carrier.

Keywords: box-ball system, RSK correspondence, tableaux, Greene's theorem

1 Introduction

A *box-ball system* (BBS) is a collection of discrete time states. At each state, we have a collection of countably many boxes with each integer from 1 to n assigned to a unique box; the remaining boxes are considered "empty." A permutation $\pi \in S_n$ gives a box-ball system state by assigning the permutation in one-line notation to the first n boxes. We apply a *BBS move* in the forward direction (letting time t increase by 1) by moving each integer from smallest to largest to the nearest empty space to its right. See Figure 1.

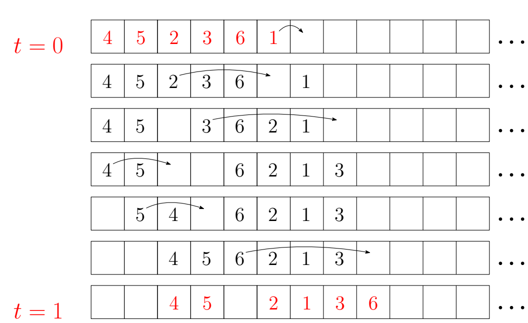

Figure 1: Performing a forward BBS move on $\pi = 452361$

A *soliton* is a consecutive increasing sequence which is preserved by all subsequent BBS moves. After a finite number of BBS moves, a box-ball system containing a configuration π will reach a *steady state*, decomposing into solitons whose sizes are weakly increasing from left to right, that is, forming an integer partition shape [7]. See Figure 2.

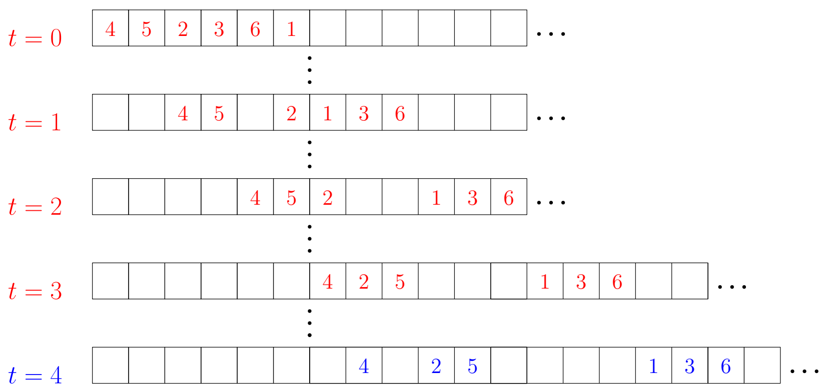

Figure 2: Forward BBS moves for $\pi = 452361$. Steady state is first achieved at $t = 3$.

From such a state, we can construct the *soliton decomposition* of a permutation, denoted SD, by stacking solitons. We obtain a tableau where each row is increasing but which may or may not be standard. For example, the soliton decomposition of the box-ball system containing $\pi = 452361$ shown in Figure 2 is

$$\mathrm{SD}(\pi) = \begin{array}{|c|c|c|} \hline 1 & 3 & 6 \\ \hline 2 & 5 \\ \cline{1-2} 4 \\ \cline{1-1} \end{array} .$$

The well-known Robinson–Schensted (RS) insertion algorithm is a bijection $\pi \mapsto (\mathrm{P}(\pi), Q(\pi))$ from S_n onto pairs of standard Young tableaux of size n, see [6]. The tableau $\mathrm{P}(\pi)$ is called the *insertion tableau* of π, and the tableau $Q(\pi)$ is called the *recording tableau* of π.

The *reading word* of a Young tableau is the permutation formed by concatenating the rows of the tableau from bottom to top. If r is the reading word of a standard Young tableau T, then $P(r) = T$.

For example, if $\pi = 452361$, then

$$\mathrm{P}(\pi) = \begin{array}{|c|c|c|} \hline 1 & 3 & 6 \\ \hline 2 & 5 \\ \cline{1-2} 4 \\ \cline{1-1} \end{array}, \quad Q(\pi) = \begin{array}{|c|c|c|} \hline 1 & 2 & 5 \\ \hline 3 & 4 \\ \cline{1-2} 6 \\ \cline{1-1} \end{array} .$$

The tableau $\mathrm{P}(\pi)$ has reading word $r = 425136$, and the insertion tableau of r is the tableau $\mathrm{P}(\pi)$.

1.1 BBS soliton partition and localized version of Greene's theorem

Greene famously showed that the RS partition of a permutation and its conjugate record the numbers of disjoint unions of increasing and decreasing sequences of the permutation [2, Theorem 3.1]. Lewis, Lyu, Pylyavskyy, and Sen recently showed that the partition shape of the soliton decomposition of a permutation and its conjugate record a pair of similar collections of permutation statistics [5, Lemma 2.1]. They studied an alternate version of the box-ball system, so we reframe their result to match our box-ball convention.

Definition 1.1. For $\pi = \pi_1 \cdots \pi_n \in S_n$ and $k \geq 1$, we define

$$I_k = \max_{\pi = u_1 | \cdots | u_k} \sum_{j=1}^{k} i(u_j),$$

where $i(u_j)$ is the length of the longest increasing subsequence in u_j and the maximum is taken over ways of writing π as a concatenation $u_1 \mid \cdots \mid u_k$ of consecutive subsequences. That is, we consider all ways to break π into k consecutive subsequences, sum the $i(u_j)$ values for each way, and let I_k be the maximum sum. We also define

$$D_k = \max_{\pi = u_1 \sqcup \cdots \sqcup u_k} \sum_{j=1}^{k} d(u_j),$$

where $d(u_j) = 1 + |\{\text{descents in } u_j\}|$ and the maximum is taken over ways to write π as the union of disjoint subsequences u_i of π. Notice that we only require $u_1, \ldots, u_k$ to be disjoint, *not* consecutive. We then form the sequences

$$\lambda_{BBS}(\pi) = (I_1, I_2 - I_1, I_3 - I_2, \ldots) \text{ and } \mu_{BBS}(\pi) = (D_1, D_2 - D_1, D_3 - D_2, \ldots).$$

Lemma 1.2 (Corollary of [5, Lemma 2.1])**.** *If $\pi \in S_n$, then the shape $\operatorname{sh}\operatorname{SD}(\pi)$ of $\operatorname{SD}(\pi)$ is equal to $\lambda_{BBS}(\pi)$. Furthermore, the conjugate of $\operatorname{sh}\operatorname{SD}(\pi)$ is equal to $\mu_{BBS}(\pi)$.*

For example, let $\pi = 521643$. Then $\lambda_{BBS}(\pi) = (2, 1, 1, 1, 1)$ and $\mu_{BBS}(\pi) = (5, 1)$. The soliton decomposition $\operatorname{SD}(\pi)$ is the (non-standard) tableau given in Figure 3.

1.2 When the soliton decomposition and RS insertion tableau coincide

We show that reading words of standard tableaux have well-behaved soliton decomposition.

Theorem 1.3. *A permutation r reaches its soliton decomposition at time $t = 0$ if and only if r is the reading word of a standard Young tableau. In particular, if r is the reading word of a standard tableau T, then $\operatorname{SD}(r) = T$ and so $\operatorname{SD}(r) = T = \operatorname{P}(r)$.*

In Section 2.1, we generalize Theorem 1.3 to standard skew tableaux.

In general, the soliton decomposition and the RS insertion tableau of a permutation do not coincide. Surprisingly, having a standard tableau for a soliton decomposition or having a soliton decomposition shape which equals the RS partition shape is enough to guarantee that the soliton decomposition and the RS insertion tableau coincide.

Theorem 1.4. *Suppose π is a permutation. Then the following are equivalent:*

1. $\mathrm{SD}(\pi) = \mathrm{P}(\pi)$.
2. $\mathrm{SD}(\pi)$ *is a standard tableau.*
3. *The shape of* $\mathrm{SD}(\pi)$ *equals the shape of* $\mathrm{P}(\pi)$.

See Section 3 for a proof of Theorem 1.4. The proof that (3) implies (2) was suggested to the authors by Darij Grinberg.

1.3 Three types of Knuth moves

The RS insertion tableau is preserved under any Knuth move [3]. In contrast, the soliton decomposition is only preserved under certain types of Knuth moves.

Definition 1.5 (Knuth Moves). Suppose $\pi, \sigma \in S_n$ and $x < y < z$.

- π and σ differ by a Knuth relation of the **first kind** (K_1) if

$$\pi = \pi_1 \ldots yxz \ldots \pi_n \text{ and } \sigma = \pi_1 \ldots yzx \ldots \pi_n$$

- π and σ differ by a Knuth relation of the **second kind** (K_2) if

$$\pi = x_1 \ldots xzy \ldots x_n \text{ and } \sigma = x_1 \ldots zxy \ldots x_n$$

- π and σ differ by Knuth relations of **both kinds** (K_B) if

$$\pi = x_1 \ldots y_1 xzy_2 \ldots x_n \text{ and } \sigma = x_1 \ldots y_1 zxy_2 \ldots x_n$$

  where $x < y_1 < z$ and $x < y_2 < z$.

Using the localized version of Greene's Theorem given in Section 1.1, we prove a partial characterization of the shape of SD in terms of types of Knuth moves.

Theorem 1.6. *If π and w are related by a sequence of K_1 or K_2 moves (but not K_B), then* $\mathrm{sh}\,\mathrm{SD}(\pi) = \mathrm{sh}\,\mathrm{SD}(w)$. *If π and w are related by a sequence of Knuth moves containing an odd number of K_B moves, then* $\mathrm{sh}\,\mathrm{SD}(\pi) \neq \mathrm{sh}\,\mathrm{SD}(w)$.

This allows us to use Knuth moves to find more permutations whose soliton decomposition and RS insertion tableau coincide.

Corollary 1.7 (Corollary of Theorem 1.4 and Theorem 1.6)**.** *If $\pi \in S_n$ is a sequence of K_1 or K_2 moves (but not K_B) away from the reading word of a standard tableau T, then $\mathrm{SD}(\pi) = \mathrm{P}(\pi) = T$. If $\pi \in S_n$ is related to the reading word of a standard tableau by a sequence of Knuth moves such that an odd number of the moves are K_B moves, then $\mathrm{SD}(\pi) \neq \mathrm{P}(\pi) = T$.*

Proposition 1.8. *Suppose $\pi \in S_n$ is the reading word of a standard tableau. Let π' be a permutation one K_1 or K_2 (but not K_B) move away from π. Then π' reaches a steady state after one BBS move.*

2 Steady states

We study the steady-state configurations and the minimum time-steps to go from a permutation to its soliton decomposition.

2.1 Standard tableaux of skew shapes

A BBS state can be represented as an array containing the integers from 1 to n as follows: scanning the boxes from right to left, each string of increasing integers becomes a row in the array. A string of k empty boxes indicates that the next row below should be shifted k steps to the left. Note that this array has increasing rows but not necessarily increasing columns; it also may not have a valid skew shape. The following is a generalization of Theorem 1.3.

Theorem 2.1. *A BBS configuration C is in steady state if and only if the associated array is a standard skew tableau whose rows are weakly decreasing in length.*

Example 2.2 (of Theorem 2.1)**.** Let $\pi = 521643$. The soliton decomposition $\mathrm{SD}(\pi)$ is the tableau given in Figure 3. Note that $C = e52e6413ee\ldots$ is a steady-state configuration (at $t = 1$), where we represent empty boxes with the symbol e. The configuration C yields the standard skew tableau in Figure 4. Conversely, if given the skew tableau in Figure 4 (with no knowledge of the original permutation), we may conclude the corresponding BBS configuration, $52e6413$, is in steady state.

1	3
4	
6	
2	
5	

Figure 3: $\mathrm{SD}(\pi)$

	1	3
	4	
	6	
2		
5		

Figure 4: Skew tableau for $C = e52e6413ee\ldots$

2.2 Permutations with n–3 time steps

We also study the relationship between the RS recording tableau of a permutation and the behavior of its box-ball system.

Definition 2.3. If $n \geq 5$, let $Q_0 := Q_0(n)$ denote the tableau

$$\begin{array}{|c|c|c|c|c|} \hline 1 & 2 & \cdots & n-2 & n-1 \\ \hline 3 & 4 \\ \cline{1-2} n \\ \cline{1-1} \end{array}.$$

Let $S_n(Q_0)$ be the set of permutations $\pi \in S_n$ such that its recording tableau $Q(\pi)$ is equal to Q_0.

Example 2.4. For $n = 5$, the five permutations of this set are the following.

45132	25143	35142	45231	35241

For $n = 6$, the sixteen permutations of this set are as follows.

451362	351462	352461	261354	461253	261453	461352	362451
251463	452361	561243	361254	561342	361452	562341	462351

Remark 2.5. It follows from Definition 2.3 that the RS algorithm induces a bijection from $S_n(Q_0)$ to the set of standard tableaux of shape $(n-3, 2, 1)$, see [9].

We define the *steady-state value* of a permutation π to be the minimum number of BBS moves required to go from π to a steady state.

Proposition 2.6. *Every permutation in $S_n(Q_0)$ has steady-state value of $n-3$.*

The following conjecture has been computationally verified up to $n = 10$.

Conjecture 2.7. *A permutation not in $S_n(Q_0)$ has steady-state value smaller than $n-3$.*

3 Proof of Theorem 1.4

3.1 Fukuda's carrier algorithm as a sequence of Knuth moves

Some of our proofs use an algorithm called the *carrier algorithm* which was first introduced in [8] and generalized in [1, Section 3.3]. It is used to calculate the $t = k+1$ state of a box-ball system given the $t = k$ state.

Let B be a box-ball configuration. By convention, let $e := n+1$. Fill a *carrier* (a sequence of n weakly increasing entries) with n copies of e. We begin the insertion process (Process 1) by putting B to the right of the carrier. We insert p, the leftmost element of B, into the carrier. Let s be the smallest entry in the carrier greater than p if such entry exists. We replace s by p and eject s from the carrier, placing it to the left of the carrier. If no entry greater than p exists in the carrier, we eject the smallest element in the carrier, and put p in the rightmost location of the carrier. We continue inserting elements of B in this manner until all non-e entries of B have been inserted into the carrier. Next, we begin the flushing process (Process 2). We eject all non-e elements in the carrier (in increasing order) by inserting e's into the carrier. This concludes one application of the carrier algorithm. The string of elements to the left of the carrier is the result of performing one box-ball move on B.

Example 3.1 (Carrier Algorithm [1])**.** We compute the $t = 3$ configuration of the box-ball system from Figure 2 by applying the carrier algorithm to the $t = 2$ configuration. We set $B := eeee452ee136\ldots$. The carrier algorithm then proceeds as follows:

begin Process 1: insertion process

$$\underbracket{eeeeee}\,eeee452ee136$$
$$e\,\underbracket{eeeeee}\,eee452ee136$$
$$\vdots$$
$$eeee\,\underbracket{eeeeee}\,452ee136$$
$$eeeee\,\underbracket{4eeeee}\,52ee136$$
$$eeeeee\,\underbracket{45eeee}\,2ee136$$
$$eeeeee4\,\underbracket{25eeee}\,ee136$$
$$eeeeee42\,\underbracket{5eeeee}\,e136$$
$$eeeeee425\,\underbracket{eeeeee}\,136$$
$$\vdots$$
$$eeeeee425eee\,\underbracket{136eee}$$

end insertion process

begin Process 2: flushing process

$$eeeeee425eee\,\underbracket{136eee} \leftarrow e$$
$$eeeeee425eee1\,\underbracket{36eeee} \leftarrow e$$
$$eeeeee425eee13\,\underbracket{6eeeee} \leftarrow e$$
$$eeeeee425eee136\,\underbracket{eeeeee}$$

end flushing process

After each insertion, the sequence in the carrier is weakly increasing.

Remark 3.2 ([1, Remark 4])**.** The carrier algorithm can be viewed as a sequence of Knuth moves. Consider the insertion of p into the carrier. If the carrier contains a number greater than p, then the insertion process is equivalent to applying a sequence of K_1 moves

$$\underbracket{\cdots s z_1 \cdots z_{l-1} z_l}\; p$$

$$\underbrace{\cdots s z_1 \cdots z_{l-1} p z_l}$$
$$\vdots$$
$$\underbrace{\cdots s p z_1 \cdots z_{l-1} z_l}$$

followed by a sequence of K_2 moves:

$$\underbrace{x_1 \cdots x_{m-1} x_m s p \cdots}$$
$$\underbrace{x_1 \cdots x_{m-1} s x_m p \cdots}$$
$$\vdots$$
$$s\, \underbrace{x_1 \cdots x_{m-1} x_m p \cdots}.$$

Otherwise, if p is greater than or equal to every element in the carrier, we apply the trivial transformation:

$$\underbrace{x \cdots}\ p$$
$$x\ \underbrace{\cdots p}.$$

Lemma 3.3 ([1, Theorem 3.1])**.** *The RS insertion tableau is a conserved quantity under the time evolution of the box-ball system, that is, it is preserved under each BBS move.*

3.2 Soliton decompositions and RSK tableaux

The following gives a characterization of permutations whose soliton decompositions are equal to their RS insertion tableaux.

Theorem 1.4. *Let π be a permutation. Then the following are equivalent:*

1. $\mathrm{SD}(\pi) = \mathrm{P}(\pi)$.
2. $\mathrm{SD}(\pi)$ *is a standard tableau.*
3. *the shape of* $\mathrm{SD}(\pi)$ *equals the shape of* $\mathrm{P}(\pi)$.

Lemma 3.4 (Due to Darij Grinberg)**.** *Suppose S is a row-strict tableau of a partition, that is, every row is increasing (with no restrictions on the columns). Let r be the reading word of the tableau S. Let $\mathrm{P}(r)$ be the RS insertion tableau of r. If the shape of S equals the shape of $\mathrm{P}(r)$, then S is standard.*

Proof of Theorem 1.4. Certainly (1) implies (2) and (3). First, we show that (2) implies (1). Suppose that $\mathrm{SD}(\pi)$ is a standard tableau. Let r denote the reading word of $\mathrm{SD}(\pi)$. We know that r is the order in which the elements of π are configured once we reach a steady state. By Lemma 3.3, $\mathrm{P}(\pi) = \mathrm{P}(r)$. Since r is the reading word of $\mathrm{SD}(\pi)$, a standard tableau, we have $\mathrm{P}(r) = \mathrm{SD}(\pi)$ by Theorem 1.3. Therefore $\mathrm{P}(\pi) = \mathrm{SD}(\pi)$.

Next, we show that (3) implies (2). Suppose that the shape of $\mathrm{SD}(\pi)$ equals the shape of $\mathrm{P}(\pi)$. Let r be the reading word of $\mathrm{SD}(\pi)$. Lemma 3.3 tells us that the RS insertion tableau is preserved under a sequence of box-ball moves, so $\mathrm{P}(\pi) = \mathrm{P}(r)$ and, in particular, $\mathrm{sh}\,\mathrm{P}(\pi) = \mathrm{sh}\,\mathrm{P}(r)$. By assumption, we have $\mathrm{sh}\,\mathrm{SD}(\pi) = \mathrm{sh}\,\mathrm{P}(r)$. Since $\mathrm{SD}(\pi)$ is a row-strict tableau and r is the reading word of $\mathrm{SD}(\pi)$, Lemma 3.4 tells us that $\mathrm{SD}(\pi)$ is standard. □

4 Multi-carrier algorithms

In this section, we give insertion algorithms that can help us study steady states and soliton decompositions.

4.1 M-carrier algorithm

In this section, we define the *M-carrier algorithm* which is equivalent to performing the carrier algorithm M times (Proposition 4.3). In addition to improving the efficiency of the box-ball system calculations, the M-carrier algorithm enables us to compare the RS-insertion algorithm and the box-ball system more directly. Given a large enough M, the M-carrier algorithm gives us an RS-like insertion algorithm which sends a permutation to its soliton decomposition.

Example 4.1. We apply the M-carrier algorithm (with $M = 3$) to $\pi = 361425$.

begin Process 1: insertion process

eeeeee eeeeee eeeeee 361425
e eeeeee eeeeee 3eeeee 61425
ee eeeeee eeeeee 36eeee 1425
eee eeeeee 3eeeee 16eeee 425
eeee eeeeee 36eeee 14eeee 25
eeeee 6eeeee 34eeee 12eeee 5
eeeee6 3eeeee 4eeee 125eee

end insertion process

begin Process 2: flushing process

eeeee6 3eeeee 4eeeee 125eee ← e
eeeee6e 34eeee 1eeeee 25eeee ← e
eeeee6e3 4eeeee 12eeee 5eeeee ← e
eeeee6e34 eeeeee 125eee eeeeee ← e
eeeee6e34e 1eeeee 25eeee eeeeee ← e
eeeee6e34ee 12eeee 5eeeee eeeeee ← e
eeeee6e34eee 125eee eeeeee eeeeee ← e
eeeee6e34eee1 25eeee eeeeee eeeeee ← e
eeeee6e34eee12 5eeeee eeeeee eeeeee ← e
eeeee6e34eee125 eeeeee eeeeee eeeeee

end flushing process

Algorithm 4.2 (The M-carrier algorithm)**.**

begin M-carrier algorithm
Set $e := n+1$
Set $B :=$ the $t=k$ configuration of the BBS
Denote B_i as the i^{th} leftmost element of B and suppose there are ℓ elements of B
Fill M adjacent carriers—depicted ⎵—with n copies of e
Denote this string of carriers $\mathcal{C}$, and the j^{th} rightmost carrier c_j
Write B to the right of $\mathcal{C}$
begin Process 1: insertion process
  for all i in $\{1,2,\ldots,\ell\}$ **do**
    Set $p := B_i$
    begin element ejection process
      for all j in $\{1,2,\ldots,M\}$ **do**
        if an element in c_j is larger than p **then**
          Set $s :=$ the smallest element in c_j larger than p
          Eject s by replacing it with p and setting $p := s$
        else
          Set $s :=$ the smallest element in c_j
          Remove s from c_j
            ▶ Note: There are now $n-1$ elements in c_j
          Place p in the rightmost location in c_j
            ▶ Note: There are now n elements in c_j
          Set $p := s$
        end if
        if $j = M$ **then**
          Place p to the left of $\mathcal{C}$
        end if
      end for
    end element ejection process
  end for
end Process 1: insertion process
begin Process 2: flushing process
  while there are non-e elements in $\mathcal{C}$ **do**
    Set $p := e$. Perform the element ejection process
  end while
end Process 2: flushing process
  ▶ Note: The elements to the left of $\mathcal{C}$ correspond to the $t = k+M$ state of the BBS
end M-carrier algorithm

Proposition 4.3. *Performing the M-carrier algorithm (with M carriers) is equivalent to perform-*

ing the 1-carrier algorithm M times. In particular, if $\pi \in S_n$, applying algorithm 4.2 to π yields the box-ball configuration of π at $t = M$.

Proof. Ejecting an element from a carrier c_i and then immediately inserting it into the next carrier c_{i+1} is equivalent to ejecting all the elements from c_i, forming a sequence and then inserting that sequence into c_{i+1}. □

4.2 Infinite-carrier algorithm

We define the *infinite-carrier algorithm* to be the same as Algorithm 4.2, but with an infinite number of carriers, so an entry is always in some carrier at every step. (This is in contrast to the M-carrier algorithm, where an entry may be ejected to the left of the carriers.) Unfortunately, it's not always possible to obtain a soliton decomposition this way.

Theorem 4.4. *Let w be a permutation and let $\sigma_1, \sigma_2, \ldots, \sigma_\ell$ be the solitons of a box-ball system containing w as a configuration.*
(1) In the infinite carrier algorithm, for each soliton σ_i, there exists a smallest positive number r_i such that, after inserting all the elements of w and r_i copies of e, the soliton σ_i is completely and solely contained in a carrier.
(2) Let $s_1, s_2, \ldots, s_\ell$ be the lengths of the respective solitons. If $\gcd(s_i, s_j)$ divides $r_i - r_j$ for all i and j, then there exists a unique number of e's (mod $\operatorname{lcm}\{s_1, s_2, \ldots, s_\ell\}$) such that the infinite carrier algorithm puts the solitons of a permutation in separate carriers (i.e., the infinite-carrier algorithm yields the box-ball soliton decomposition of w).

Example 4.5. Let $\pi = 24513$. The box-ball system containing π has solitons 135 and 24, which have lengths 3 and 2 respectively (with $\operatorname{lcm}\{3, 2\} = 6$). Since all the (pairwise) greatest common divisors of the soliton lengths are 1, there exists a unique number (0) of e's (mod 6) such that the infinite carrier algorithm puts the solitons of a permutation in separate carriers. In the infinite-carrier algorithm, immediately after all entries of π and $0 + 6k$ copies of e's are inserted, the solitons of π are sorted into separate carriers:

begin Process 1: insertion process

... *eeeee* *eeeee* 24513

... *eeeee* 2*eeee* 4513

... *eeeee* 24*eee* 513

... *eeeee* 245*ee* 13

... *eeeee* 2*eeee* 145*ee* 3

... *eeeee* **24***eee* **135***ee*

end insertion process

begin Process 2: flushing process

... *eeeee* *eeeee* **24***eee* **135***ee* ← *e* #1

... *eeeee* 2*eeee* 14*eee* 35*eee* ← *e* #2

... *eeeee* 24*eee* 13*eee* 5*eeee* ← *e* #3

... *eeeee* 2*eeee* 4*eeee* 135*ee* *eeeee* ← *e* #4

... *eeeee* 24*eee* 1*eeee* 35*eee* *eeeee* ← *e* #5

... *eeeee* 2*eeee* 4*eeee* 13*eee* 5*eeee* *eeeee* ← *e* #6

... *eeeee* **24***eee* *eeeee* **135***ee* *eeeee* *eeeee* ← *e* #7

⋮ ⋮

end flushing process

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