

# Checking Big Suffix and LCP Arrays by Probabilistic Methods

Yi Wu, Ge Nong, Wai Hong Chan, Ling Bo Han

**Abstract**—For full-text indexing of massive data, the suffix and LCP (longest common prefix) arrays have been recognized as the fundamental data structures and should be verified to ensure their correctness after construction. We propose in this paper two methods to probabilistically check the suffix and LCP arrays in external memory by using a Karp-Rabin fingerprinting function, in terms of that the checking result is wrong with only a negligible probability. The first method checks the lexical order and the LCP-value of two neighboring suffixes in the given suffix array by computing and comparing the fingerprints of their LCPs. The second method first applies the same technique to check a subset of the suffix and LCP arrays, and then checks the remaining when augmenting them from the verified part following the induced-sorting principle. The experimental results indicate that, xxx.

**Index Terms**—Suffix and LCP arrays, verification, Karp-Rabin fingerprinting function.



## 1 INTRODUCTION

### 1.1 Background

Suffix and longest common prefix (LCP) arrays play an important role in various string processing tasks, such as data compression, pattern matching and genome assembly. In dozens of applications, these two data structures are combined to constitute a powerful full-text index for massive data, called enhanced suffix array [1], which is more space efficient than suffix tree and applicable to emulating any searching functionalities provided by the latter in the same time complexity. During the past decades, much effort has been put on the development of designing efficient suffix array construction algorithms (SACAs). Specifically, the first internal-memory algorithm for building SA was introduced in [2]. From then on, a plethora of SACAs have been proposed on different computation models, e.g., internal memory [3], [4], [5], [6], external memory [7], [8], [9], [10], [11], [12], [13] and shared memory models [14], [15], [16], [17]. In respect of the design on LCP-array construction algorithms (LACAs), the existing works can be classified into two categories, where the algorithms of the first category compute the suffix and LCP arrays in the same time [10], [18], [19] and that of the second category take the suffix array (SA) and/or Burrows-Wheeler transform (BWT) as input to facilitate the computation [15], [18], [20], [21], [22], [22], [23].

While the study for efficient construction of suffix and LCP arrays is evolving, the programs implementing the proposed algorithms are commonly provided “as is”, with the purpose only for the performance evaluation experiments of the articles where they are reported. That is, these pro-

grams give no guarantee that they have correctly implemented the proposed algorithms. The programs for recently proposed algorithms are becoming much more complicated than before, causing more difficulties for program verifying and debugging<sup>1</sup>. As a common practice, a suffix or LCP array checker is also provided for verifying the correctness of a constructed array. For example, such a checker is provided in the software packages eSAIS [?] (DC3, pScan and etc? more and better) for constructing suffix and/or LCP arrays. In addition to help avoid implementation bugs, a checker is also demanded for an array constructed by a probabilistic algorithm [?]. In this case, the array is correct with a probability and hence must be verified by a checker to ensure its correctness.

As far as we know, the work presented in [24] is the only SA checking method that can be found in the existing literature, and no efficient approach for the LCP-array verification has been reported yet. In particular, there is currently no reported solution that can check both the suffix and the LCP arrays in external memory. This motivates our work here to design efficient external memory algorithms for checking the suffix and LCP arrays of massive data.

### 1.2 Contribution

The contribution in this paper mainly includes two methods for checking the given suffix and LCP arrays in external memory, where both methods work for constant alphabets and the former can be also applied to integer ones.

In principle, the first method checks the lexical order and the LCP-value of two neighboring suffixes in the suffix array by literally comparing their characters in sequence. To reduce time complexity for the string comparison, a Karp-Rabin fingerprinting function is employed to transform each involved comparand into a single integer, called fingerprint, and the fingerprints are compared to correctly check the equality of their prototypes with a negligible error

1. In our studies before, we have experienced problems caused by bugs of the existing programs.

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probability. We will demonstrate that all the fingerprints in need can be calculated using linear time when scanning the input string. The experimental results indicate that the space efficiency remains invariant with the increasing of input size, while both time and I/O consumptions grows linearly under the same circumstances.

The second method verifies the two arrays following the induced-sorting principle.

The second method verifies the two arrays following the induced-sorting principle, which was formerly proposed for building suffix and LCP arrays in both internal and external memory.

This technique is also employed in the second method. The second method is adapted from the induced-sorting principle.

The second method checks both suffix and LCP arrays based on the induced-sorting principle. The main idea is to first check a subset of the suffix and LCP arrays and then verify the inducing process to ensure the correctness of the final suffix and LCP arrays augmented from the subset. Different from the previous method, it can be also integrated into any algorithm for inducing suffix and LCP arrays to build and check the arrays simultaneously.

The remainder of this paper is organized as follows. We describe the proposed methods and algorithms in Sections 2 and 3, then present the experimental results in Section 4, and give the conclusion in Section 5.

**A suggested paper's framework:**

1. The straightforward algorithm for computing and comparing the FPs of each pair of neighboring items in the LCP array, for checking both the SA and the LCP arrays.

The drawback is space consuming, to be overcome by the algorithms proposed in the rest of this article...

2. The method for building and checking simultaneously, for the suffix and LCP arrays constructed by induced sorting.

The principle of induced sorting is explained here.

The drawback is that it is applicable only for an array built by induced sorting, to be overcome by further extending the idea to check any given array.

3. Extend the 2nd method to check any given suffix or LCP arrays.

4. Experiments

5. Conclusion

## 2 METHOD A

### 2.1 Notations

Given an input string  $x[0, n)$  drawn from an alphabet  $\Sigma$ , we say  $x[i, j]$  is a substring of  $x$  that starts with  $x[i]$  and ends with  $x[j]$ . Particularly,  $x[i, j]$  is a suffix of  $x$  if  $j = n - 1$ . For short, we denote  $x[i, n)$  by  $\text{suf}(i)$ .

The suffix array of  $x$ , denoted by  $sa$ , is a permutation of  $\{0, 1, \dots, n - 1\}$  such that  $\text{suf}(sa[i])$  is lexicographically greater than  $\text{suf}(sa[i - 1])$  for all  $i \in [1, n)$ .

The LCP array of  $x$ , denoted by  $lcp$ , is composed of  $n$  integers, where  $lcp[0] = 0$  and  $lcp[i]$  equals to the length of LCP of  $\text{suf}(sa[i])$  and  $\text{suf}(sa[i - 1])$  for all  $i \in [1, n)$ , i.e., the first  $lcp[i]$  characters of  $\text{suf}(sa[i])$  and  $\text{suf}(sa[i - 1])$  are identical and the  $(lcp[i] + 1)$ -th characters of two suffixes are different. For notation convenience, we refer the length of an LCP as LCP value or LCP length.

### 2.2 Main Idea

We first present in Lemma 1 the conditions that are sufficient and necessary for checking the suffix and LCP arrays. Specifically, condition (1) demonstrates that all the suffixes in  $x$  are sorted in  $sa$ , while conditions (2)-(3) indicate that the order and the LCP value of any two neighboring suffixes in  $sa$  are both correct.

**Lemma 1.** Both  $sa[0, n)$  and  $lcp[0, n)$  are correct if and only if the following conditions are satisfied, for all  $i \in [1, n)$ :

- (1)  $sa$  is a permutation of  $\{0, 1, \dots, n - 1\}$ .
- (2)  $x[sa[i], sa[i] + lcp[i] - 1] = x[sa[i - 1], sa[i - 1] + lcp[i] - 1]$ .
- (3)  $x[sa[i] + lcp[i]] > x[sa[i - 1] + lcp[i]]$ .

*Proof:* Both the sufficiency and necessity are immediately seen from the definition of suffix and LCP arrays.  $\square$

Obviously, we can generalize Lemma 1 to check any subset of  $sa$  and  $lcp$ . Besides, given that  $sa$  or  $lcp$  is correct, this lemma can be used to check  $lcp$  or  $sa$  alone as well.

For each pair of neighboring suffixes in  $sa$ , say  $\text{suf}(sa[i])$  and  $\text{suf}(sa[i + 1])$ , it takes at worst  $\mathcal{O}(n)$  time to perform a character-wise string comparison for checking their leftmost  $lcp[i]$  characters. An alternative is to compare the two sequences of characters by their hash values in constant time. This can be done using a perfect hash function (PHF) that maps two strings to an identical integer if and only if they are literally equal to each other. However, the cost of finding a PHF is non-negligible in practice, thus we prefer to use the Karp-Rabin fingerprinting function [25] for conducting the string-to-integer transformations mentioned above. Concretely, given a prime  $L$  and an integer  $\delta \in [1, L)$ , the fingerprint of a substring  $x[i, j]$ , denoted by  $\text{fp}(i, j)$ , can be calculated according to the following two formulas:

**Formula 1.**  $\text{fp}(0, i) = \text{fp}(0, i - 1) \cdot \delta + x[i] \pmod L$  for  $i \geq 0$ , or  $\text{fp}(0, i) = 0$  for  $i < 0$ .

**Formula 2.**  $\text{fp}(i, j) = \text{fp}(0, j) - \text{fp}(0, i - 1) \cdot \delta^{j-i+1} \pmod L$ .

Notice that two equal substrings always have a common fingerprint, but the inverse is not true. Fortunately, it has been proved that the probability of a false match can be reduced to a negligible level by setting  $L$  properly [25]. This property is utilized in [26] to design a probabilistic algorithm for computing a sparse suffix array. Using the fingerprinting function, we have Corollary 1.

**Corollary 1.** Both  $sa[0, n)$  and  $lcp[0, n)$  are correct with a high probability given the following conditions, for all  $i \in [1, n)$ :

- (1)  $sa$  is a permutation of  $\{0, 1, \dots, n - 1\}$ .
- (2)  $\text{fp}(sa[i], sa[i] + lcp[i] - 1) = \text{fp}(sa[i - 1], sa[i - 1] + lcp[i] - 1)$ .
- (3)  $x[sa[i] + lcp[i]] > x[sa[i - 1] + lcp[i]]$ .

### 2.3 Algorithm

We design Algorithm 1 to check the conditions in Corollary 1. This algorithm mainly consists of three steps and each step is explained detailedly in the following paragraphs.

**Step 1.** The first step can be divided into three substeps:

- (1a) Scan  $sa$  and  $lcp$  rightward with  $i$  increasing from 1 to  $n - 1$ . For each scanned  $\langle sa[i], lcp[i] \rangle$ , create an AITEM

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**Algorithm 1:** The algorithm using Method A.

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**Input:**  $x, sa, lcp$

Step 1. Compute  $fp(sa[i], sa[i] + lcp[i] - 1)$  and retrieve  $x[sa[i] + lcp[i]]$  for  $i \in [1, n)$ .

Step 2. Compute  $fp(sa[i], sa[i] + lcp[i + 1] - 1)$  and retrieve  $x[sa[i] + lcp[i + 1]]$  for  $i \in [0, n - 1)$ .

Step 3. Check if  $fp(sa[i], sa[i] + lcp[i] - 1) = fp(sa[i - 1], sa[i - 1] + lcp[i] - 1)$  and  $x[sa[i] + lcp[i]] > x[sa[i - 1] + lcp[i]]$  for  $i \in [1, n)$ .

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with  $idx = i, pos = sa[i], lv = lcp[i]$ . Sort the items by  $pos$  in ascending order.

- (1b) Scan  $x$  rightward with  $p$  increasing from 0 to  $n - 1$ . For each scanned  $x[p]$ , compute  $fp(0, p)$  and update all the AITEMs with  $pos = p + 1$  by setting  $fp = fp(0, p)$  and  $pos = pos + lv$ . Sort the items by  $pos$  in ascending order.
- (1c) Scan  $x$  rightward with  $p$  increasing from 0 to  $n - 1$ . For each scanned  $x[p]$ , compute  $fp(0, p)$  and update all the AITEMs with  $pos = p + 1$  by setting  $fp = fp(0, p) - fp \cdot \delta^{lv} \bmod L$  and  $ch = x[p + 1]$ . Sort the items by  $idx$  in ascending order.

An auxiliary data structure called AITEM is introduced to facilitate the computation of fingerprints, where each AITEM is a 5-tuple  $\langle idx, pos, lv, ch, fp \rangle$  for a suffix. To enable fast calculation of  $fp(sa[i] - 1) / fp(sa[i] + lcp[i] - 1)$  for all  $i \in [1, n)$ , step 2 first sorts the AITEMs by  $pos$  and then sequentially retrieves  $fp(0, pos)$  for each item by iteratively computing  $\{fp(0, 0), fp(0, 1), \dots, fp(0, n - 1)\}$  according to Formula 1. Given that  $fp(sa[i] - 1)$  and  $fp(sa[i] + lcp[i] - 1)$  are already known,  $fp(sa[i], sa[i] + lcp[i] - 1)$  is obtained according to Formula 2.

Notice that all the AITEMs are sorted by the starting positions of the corresponding suffixes in substep (1a). Thus, we check condition (1) of Corollary 1 during the time when sequentially accessing the items in substep (1b).

**Step 2.** This step computes  $fp(sa[i], sa[i] + lcp[i + 1] - 1)$  for  $i \in [0, n - 1)$  using the following three substeps:

- (2a) Scan  $sa$  and  $lcp$  rightward with  $i$  increasing from 0 to  $n - 2$ . For each scanned  $\langle sa[i], lcp[i + 1] \rangle$ , create an AITEM with  $idx = i, pos = sa[i], lv = lcp[i + 1]$ . Sort the items by  $pos$  in ascending order.
- (2b) Reuse step (1b) to update and sort AITEMs.
- (2c) Reuse step (1c) to update and sort AITEMs.

The major difference between the first two steps lies in that, the field  $lv$  of the AITEMs for  $suf(sa[i])$  are respectively set as  $lcp[i]$  and  $lcp[i + 1]$  in substeps (1a) and (2a).

**Step 3.** Let  $arrA$  and  $arrB$  denote the arrays of AITEMs produced by steps 1 and 2, respectively. Scan  $arrA$  and  $arrB$  rightward with  $i$  increasing from 0 to  $n - 2$ . For each pair  $\langle arrA[i], arrB[i] \rangle$ , check if  $arrA[i].fp = arrB[i].fp$  and  $arrA[i].ch > arrB[i].ch$  to ensure the correctness of conditions (2)-(3) in Corollary 1.

## 2.4 Substring Fingerprint

Algorithm 1 computes  $fp(i, j)$  from  $fp(0, i - 1)$  and  $fp(0, j)$  according to Formula 2. Let  $e$  denote  $j - i + 1$ , then the coefficient  $(\delta^e \bmod L)$  must be calculated quickly or it will become a performance bottleneck. One approach first decomposes  $e$  into  $k_1 \cdot m + k_2$  and then computes  $\delta^e$  by multiplying  $\delta^{k_1 \cdot m}$  and  $\delta^{k_2}$ , where  $k_1, k_2$  are integers and

$k_1 \in [0, \lceil \frac{n}{m} \rceil], k_2 \in [0, m)$ . An alternative first decomposes  $e$  into  $\sum_{i=0}^{\lceil \log 2^n \rceil} k_i \cdot 2^i$  and then computes  $\prod_{i=0}^{\lceil \log 2^n \rceil} \delta^{k_i \cdot 2^i}$  to obtain  $\delta^e$ , where  $k_i \in \{0, 1\}$ . The first approach answers in  $O(1)$  time and consumes  $O(m + \lceil \frac{n}{m} \rceil)$  space to maintain two lookup tables for storing  $\{\delta^0, \delta^m, \dots, \delta^{\lceil \frac{n}{m} \rceil m}\}$  and  $\{\delta^0, \delta^1, \dots, \delta^{m-1}\}$ , respectively, while the second approach answers in  $O(\lceil \log 2^n \rceil)$  time and consumes  $O(\lceil \log 2^n \rceil)$  space to store  $\{\delta^1, \delta^2, \dots, \delta^{2^{\lceil \log 2^n \rceil}}\}$ . For a better space performance, we adopt the second approach to compute the fingerprints in our implementation for the algorithm.

## 2.5 Analysis

Algorithm 1 performs multiple scans and sorts for fixed-size objects with integer keys. Consider an external memory model with RAM size  $M$ , disk size  $D$  and block size  $B$ , all are in words, then the time and I/O complexities for a scan are  $O(n)$  and  $O(n/B)$ , respectively, while those for an integer sort are  $O(n \log_{M/B}(n/B))$  and  $O((n/B) \log_{M/B}(n/B))$ , respectively [27]. Besides, the algorithm reaches its peak disk use when sorting  $n$  AITEMs in external memory during the second step. Given that each input character occupies  $a$  words and each fingerprint occupies  $b$  words, the space consumption for each sort is  $(a + b + 3)n$  words.

## 2.6 Example

## 3 METHOD B

As we will see from the experimental study in Section 4, Algorithm 1 designed by Method A is quite space consuming, the peak disk use is 40 bytes per input character. This motivates us to design a lightweight checker that uses less space. In this section, we propose a method for checking the suffix and LCP arrays using the induced-sorting principle. The experimental results show that Algorithm 3 designed by this method consumes about 40% less space than Algorithm 1 on real-world data.

## 3.1 Notations

Assume  $x[n - 1]$  is lexicographically the smallest character in  $\Sigma$  and appears in  $x[0, n)$  only once, we introduce the following notations and symbols for description clarity.

*L-type/S-type/LMS character and suffix.* All the characters in  $x$  are classified into three different types, namely L-type, S-type and LMS. In details,  $x[i]$  is S-type if (1)  $i = n - 1$  or (2)  $x[i] < x[i + 1]$  or (3)  $x[i] = x[i + 1]$  and  $x[i + 1]$  is S-type; otherwise,  $x[i]$  is L-type. In particular, if  $x[i - 1]$  and  $x[i]$  are respectively L-type and S-type, then  $x[i]$  is LMS. Furthermore,  $suf(i)$  is L-type, S-type or LMS if  $x[i]$  is L-type, S-type or LMS, respectively.

*L-type/S-type/LMS substring.* Suppose  $x[j]$  is LMS and no characters in  $x[i+1, j-1]$  are LMS, then substring  $x[i, j]$  is an L-type, S-type or LMS substring if  $x[i]$  is L-type, S-type or LMS, respectively.

*Suffix buckets.* Suffixes in  $sa$  are naturally grouped into multiple buckets, where each bucket occupies a contiguous interval of  $sa$  and contains all the suffixes with an identical heading character. Besides, a bucket can be further divided into two parts, where the left/right part is a subbucket containing only L-type/S-type suffixes. For short, we use  $sa\_bkt(c)$  to denote the bucket containing all the suffixes with a heading character  $c$ , and  $sa\_bkt_L(c)/sa\_bkt_S(c)$  to denote the left/right subbucket in  $sa\_bkt(c)$ .

*LCP buckets.* Suppose  $sa\_bkt(c)$  is a suffix bucket ranging from  $sa[i]$  to  $sa[j]$ , then  $lcp[i, j]$  is the corresponding LCP bucket, denoted by  $lcp\_bkt(c)$ , and it can be further divided into two subbuckets  $lcp\_bkt_L(c)$  and  $lcp\_bkt_S(c)$  according to  $sa\_bkt_L(c)$  and  $sa\_bkt_S(c)$ .

*Character repetition count.* Suppose  $x[i] = x[i+1] = \dots = x[j]$  and  $x[j] \neq x[j+1]$ , then  $j-i+1$  is the number of successive repetitions for  $x[i]$ . Let  $rep(i)$  denote the value.

*Inverse suffix array.* The inverse suffix array  $isa$  satisfies that  $isa[sa[i]] = i$  for  $i \in [0, n)$ .

*Reduced string.* The reduced string  $x_1$  records the names of LMS suffixes, where each name represents the relative order of the corresponding suffix among all the LMS ones.

*Position array.* The position array  $pa$  records the starting positions of LMS suffixes.

*Type array.* The type array  $t$  records the types of characters in  $x$ . Let  $t[i] = 0$  or  $1$  if  $x[i]$  is L-type or S-type, respectively.

In addition, we denote the suffix and LCP arrays of LMS suffixes by  $sa_{LMS}$  and  $lcp_{LMS}$ .

### 3.2 An Overview of Inducing LCP Array

An induced-sorting SACA (e.g., [6]) mainly consists of a reduction phase followed by an induction phase. In brief, it first sorts and names the LMS substrings to produce the reduced string  $x_1$  during the reduction phase and then determines whether there exist two equal characters in  $x_1$ . If yes, then it recursively performs the reduction phase by replacing  $x$  with  $x_1$ ; otherwise, it computes  $sa_1$  from  $x_1$  and performs the induction phase to induce  $sa$  from  $sa_1$ . The work presented in [18] shows that an induced-sorting SACA can be modified to design an LACA for constructing the suffix and LCP arrays simultaneously, which principle is explained here for readers to understand our method. Its main idea is to compute the LCP value of two suffixes placed at the neighboring positions in the same subbucket according to the following properties, where  $suf(sa[j])$  and  $suf(sa[k])$  are the suffixes from which induce  $suf(sa[i-1])$  and  $suf(sa[i])$  during the induction phase.

**Property 1.** If  $x[sa[i]] = x[sa[i-1]]$ ,  $t[sa[i]] = t[sa[i-1]]$  and  $x[sa[j]] \neq x[sa[k]]$ , then  $lcp[i] = 1$ .

**Property 2.** If  $x[sa[i]] = x[sa[i-1]]$ ,  $t[sa[i]] = t[sa[i-1]]$  and  $x[sa[j]] = x[sa[k]]$ , then  $lcp[i] = 1 + \min(lcp[j+1], lcp[j+2], \dots, lcp[k])$ .

Algorithm 2 summarizes the main steps of the induction phase of the induced-sorting LACA in [18]. Suppose  $sa_{LMS}$

and  $lcp_{LMS}$  have been computed and their elements are inserted into the corresponding buckets in  $sa$  and  $lcp$ , the last two steps of the algorithm are described below.

S3. Clear  $sa\_bkt_L(c)/lcp\_bkt_L(c)$  for  $c \in \Sigma$  in  $sa/lcp$ .

- (1) Scan  $sa$  rightward with  $i$  increasing from 0 to  $n-1$ . For each scanned item  $sa[i]$ , insert  $sa[i]-1$  into the leftmost empty position of  $sa\_bkt_L(x[sa[i]-1])$  if  $t[sa[i]-1] = 0$ .
- (2) For each induced item placed in  $sa[i]$ : set  $lcp[i] = 0$  if  $x[sa[i]] \neq x[sa[i-1]]$ ; otherwise, compute  $lcp[i]$  following Properties 1-2.

S4. Clear  $sa\_bkt_S(c)/lcp\_bkt_S(c)$  for  $c \in \Sigma$  in  $sa/lcp$ .

- (1) Scan  $sa$  leftward with  $i$  decreasing from  $n-1$  to 0. For each scanned item  $sa[i]$ , insert  $sa[i]-1$  into the rightmost empty position of  $sa\_bkt_S(x[sa[i]-1])$  if  $t[sa[i]-1] = 1$ .
- (2) For each induced item placed in  $sa[i-1]$ : if  $x[sa[i]] = x[sa[i-1]]$  and  $t[sa[i]] = t[sa[i-1]]$ , then compute  $lcp[i]$  following Properties 1-2.

There remain two special cases needing to be handled separately. When inducing L-type suffixes in S3, the LCP value of the rightmost L-type and the leftmost LMS suffixes in the same bucket, say  $suf(sa[i_1])$  and  $suf(sa[i_2])$ , is equal to  $\min(rep(sa[i_1]), rep(sa[i_2]))$ . Likewise, when inducing S-type suffixes in S4, the LCP value of the rightmost L-type and the leftmost S-type suffixes in the same bucket is computed following the same way. Notice that,  $rep(sa[i_1])/rep(sa[i_2])$  is calculated by literally comparing the characters in the suffix from left to right. It is revealed in [18] that, a repetition interval cannot stride over two successive LMS substrings, thus all the involved comparisons can be done in overall linear running time.

### 3.3 Check LCP Array

The inducing process of the LCP array in Section 3.2 also constitutes the sufficient and necessary conditions for a correct  $lcp$  as stated below.

**Lemma 2.** Given that  $sa$  is correct,  $lcp$  is correct if and only if:

- (1)  $lcp_{LMS}$  is correct.
- (2)  $lcp[i]$  is equal to the value calculated by the inducing process in Section 3.2, for  $i \in [0, n)$ .

This lemma suggests a method to check an LCP array as follows. We address two cases: (1) given  $lcp_{LMS}$  and correct  $sa$ , to build and check  $lcp$  simultaneously; (2) given  $lcp$  and correct  $sa$ , to check  $lcp$ .

Notice that the processes for inducing and checking  $lcp$  are essentially the same in terms of that both utilize condition (2) in Lemma 2, the only difference is that the former computes  $lcp[i]$  using the condition but the latter checks if the condition is held for each given  $lcp[i]$ .

**Case 1.** In the first case, we first check  $lcp_{LMS}$  by Method A, then induce and check  $lcp$  from  $lcp_{LMS}$  simultaneously. The problem to be solved is that when an item is induced into a bucket, its corresponding item  $lcp[i]$  to be compared is not known yet. Our solution for this is to integrate the processes of inducing and checking into a single one, by ensuring the sequence of items induced into a bucket in  $lcp$

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**Algorithm 2:** The algorithm of the induction phase for an induced-sorting LACA.

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**Input:**  $x, sa_1, lcp_1$

**Output:**  $sa, lcp$

- S1. Compute  $sa_{LMS}$  and  $lcp_{LMS}$  from  $sa_1$  and  $lcp_1$ , respectively.
  - S2. Insert items of  $sa_{LMS}$  and  $lcp_{LMS}$  into  $sa$  and  $lcp$ .
  - S3. Induce L-type suffixes and LCP lengths.
  - S4. Induce S-type suffixes and LCP lengths.
- 

in the inducing process is identical to that later seen by the scanning process that is also the checking process. For each bucket, we increasingly compute the fingerprints of both sequences and check their equality during the whole process for inducing  $lcp$ . If the two fingerprints for each bucket are equal, then the condition (2) of Lemma 2 will be seen by the checking process with a high probability. As a result,  $lcp$  can be built and probabilistically checked in the same time using this method, for this we have Corollary 2.

**Corollary 2.** Given that  $sa$  is correct, then  $lcp$  is correct with a high probability if and only if these conditions are satisfied for all  $c \in \Sigma$ :

- (1)  $lcp_{LMS}$  is correct.
- (2) The fingerprints of  $lcp_{L1}(c)$  and  $lcp_{L2}(c)$  are equal.
- (3) The fingerprints of  $lcp_{S2}(c)$  and  $lcp_{S1}(c)$  are equal.

For each  $c$ ,  $lcp_{L2}(c)/lcp_{S2}(c)$  or  $lcp_{L1}(c)/lcp_{S1}(c)$  records the sequences of items in  $lcp\_bkt_L(c)/lcp\_bkt_S(c)$  in their order of being scanned or induced, respectively. We augment S3 and S4 of Algorithm 2 to compute the fingerprints of these sequences as follows:

S3'. Initialize  $fp(lcp_{L1}(c)) = 0$  and  $fp(lcp_{L2}(c)) = 0$ .

- (1) For each scanned item  $sa[i]$ , update  $fp(lcp_{L2}(c))$  by  $lcp[i]$  if  $x[sa[i]] = c$  and  $t[sa[i]] = 0$ .
- (2) For each induced item placed in  $sa[i]$ , update  $fp(lcp_{L1}(c))$  by  $lv$  if  $x[sa[i]] = c$ , where  $lv$  is the calculated LCP value.

S4'. Initialize  $fp(lcp_{S1}(c)) = 0$  and  $fp(lcp_{S2}(c)) = 0$ .

- (1) For each scanned item  $sa[i]$ , update  $fp(lcp_{S2}(c))$  by  $lcp[i]$  if  $x[sa[i]] = x[sa[i-1]] = c$  and  $t[sa[i]] = t[sa[i-1]] = 1$ .
- (2) For each induced item placed at  $sa[i-1]$ , update  $lcp_{S1}(c)$  by  $lv$  if  $x[sa[i-1]] = x[sa[i]] = c$  and  $t[sa[i-1]] = t[sa[i]] = 1$ , where  $lv$  is the calculated LCP value.

We generalize Formula 1 in Section 2.2 to iteratively compute the fingerprint of each sequence in steps S3' and S4'. Specifically, when a new item  $e$  is appended to a sequence, its fingerprint  $fp$  is updated according to the formula  $fp = fp \cdot \delta + e \mod L$ .

**Case 2.** In the second case, we first scan  $lcp$  to compute  $lcp_{LMS}$  and check  $lcp_{LMS}$  by Method A, then induce and check the LCP array from  $lcp_{LMS}$  following the same idea of the first case. After that, we compare the given  $lcp$  with the induced LCP array to ensure the correctness of the former.

### 3.4 Check Suffix Array

An induced-sorting SACA determines the order of two suffixes by comparing their heading characters and succeeding suffixes in  $x$ . In other words, Property 3 is held for any

two suffixes placed in  $sa[i]$  and  $sa[j]$ , where  $\text{suf}(sa[p])$  and  $\text{suf}(sa[q])$  are the two suffixes from which induce  $\text{suf}(sa[i])$  and  $\text{suf}(sa[j])$  during the induction phase.

**Property 3.** If  $(x[sa[i]], p) > (x[sa[j]], q)$ , then  $i > j$ .

As shown below, Property 3 can be used to constitute the sufficient and necessary conditions for a correct  $sa$ .

**Lemma 3.**  $sa$  is correct if and only if:

- (1)  $sa_{LMS}$  is correct.
- (2)  $i > j$  if  $(x[sa[i]], p) > (x[sa[j]], q)$ , for  $i, j \in [0, n)$ .

We use Lemma 3 to check a suffix array in two cases: (1) given  $sa_{LMS}$ , to build and check  $sa$  in the same time; (2) given  $sa$ , to check  $sa$ .

**Case 1.** In the first case, we first check  $sa_{LMS}$  by using Method A, and then induce and check  $sa$  from  $sa_{LMS}$  by comparing the fingerprint of the sequence of items induced into a bucket with that of the sequence of items scanned in the bucket. If the two fingerprints are equal for each bucket, then the condition (2) of Lemma 3 are satisfied with a high probability. Following the discussion, we have Corollary 3.

**Corollary 3.**  $sa$  is correct with a high probability if and only if these conditions are satisfied for all  $c \in \Sigma$ :

- (1)  $sa_{LMS}$  is correct.
- (2) The fingerprints of  $sa_{L1}(c)$  and  $sa_{L2}(c)$  are equal.
- (3) The fingerprints of  $sa_{S2}(c)$  and  $sa_{S1}(c)$  are equal.

For each  $c$ ,  $sa_{L2}(c)/sa_{S2}(c)$  or  $sa_{L1}(c)/sa_{S1}(c)$  records the sequence of items in  $sa\_bkt_L/sa\_bkt_S$  in their order of being scanned or induced, respectively. Similar to S3' and S4', we compute the fingerprints of these sequences by augmenting the last two steps of Algorithm 2 as follows:

S3''. Initialize  $fp(sa_{L1}(c)) = 0$  and  $fp(sa_{L2}(c)) = 0$ .

- (1) For each scanned item  $sa[i]$ , update  $fp(sa_{L2}(c))$  by  $sa[i]$  if  $x[sa[i]] = c$  and  $t[sa[i]] = 0$ .
- (2) For each induced item, update  $fp(sa_{L1}(c))$  by  $sa[j]-1$  if  $x[sa[j]-1] = c$ , where  $sa[j]$  is the starting position of the suffix from which induces the item.

S4''. Initialize  $fp(sa_{S1}(c)) = 0$  and  $fp(sa_{S2}(c)) = 0$ .

- (1) For each scanned item  $sa[i]$ , update  $fp(sa_{S2}(c))$  by  $sa[i]$  if  $x[sa[i]] = c$  and  $t[sa[i]] = 1$ .
- (2) For each induced item, update  $fp(sa_{S1}(c))$  by  $sa[j]-1$  if  $x[sa[j]-1] = c$ , where  $sa[j]$  is the starting position of the suffix from which induces the item.

**Case 2.** In the second case, we first scan  $sa$  to compute  $sa_{LMS}$  and check  $sa_{LMS}$  by using Method A, then induce and check the suffix array from  $sa_{LMS}$  following the same idea of the first case. Afterward, we compare the given  $sa$  with the induced suffix array to ensure the correctness of the former.

### 3.5 Algorithms

We propose two external-memory algorithms based on the method described in Sections 3.3-3.4. The first algorithm can build and check the suffix and LCP arrays simultaneously, while the second algorithm, called Algorithm 3, can check the two arrays after their construction.

#### 3.5.1 Build and Check Simultaneously

We adapt Algorithm 2 to check the conditions of Corollaries 2-3 when building the suffix and LCP arrays by an induced-sorting LACA.

There are three places needed to be revised in Algorithm 2. The first place is to check  $sa_{LMS}$  and  $lcp_{LMS}$  using Algorithm 1 after computing them in S1. The second place is to compute the fingerprints by adapting S3 and S4 of Algorithm 2 as below:

- (1) Augment S3 with S3' and S3'' to compute the fingerprints of  $fp(lcp_{L1}(c)/lcp_{L2}(c))$  and  $fp(sa_{L1}(c)/sa_{L2}(c))$  for all  $c \in \Sigma$ .
- (2) Augment S4 with S4' and S4'' to compute the fingerprints of  $fp(lcp_{S1}(c)/lcp_{S2}(c))$  and  $fp(sa_{S1}(c)/sa_{S2}(c))$  for all  $c \in \Sigma$ .

The third place is to compare the fingerprints after the inducing process.

This algorithm can be applied to the external memory model if we extend Algorithm 2 for inducing the suffix and LCP arrays using external memory by the method described in [10].

#### 3.5.2 Build and Check Sequentially

Algorithm 3 mainly consists of three steps. In the first step, it computes  $sa_{LMS}$  and  $lcp_{LMS}$  from  $sa$  and  $lcp$ , and ensures their correctness by using Algorithm 1. In the second step, it checks the conditions of Corollaries 2-3 to verify the suffix and LCP arrays induced from  $sa_{LMS}$  and  $lcp_{LMS}$ . In the last step, it checks the given  $sa$  and  $lcp$  by comparing them with the induced suffix and LCP arrays. In what follows, we explain the algorithm step by step in more details for better understanding.

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**Algorithm 3:** The algorithm that performs verification after construction using Method B.

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**Input:**  $x, sa, lcp$

Step 1. Compute and check  $sa_{LMS}$  and  $lcp_{LMS}$ .

Step 2. Induce and check the suffix and LCP arrays from  $sa_{LMS}$  and  $lcp_{LMS}$ .

Step 3. Check  $sa$  and  $lcp$  by comparing them with the induced suffix and LCP arrays.

---

**Step 1.** This step computes  $sa_{LMS}$  and  $lcp_{LMS}$  from  $sa$  and  $lcp$  by the following three substeps:

- (1a) Sort  $i$  by  $sa[i]$  for  $i \in [0, n)$  to produce  $isa$ .
- (1b) Sort  $\langle x[i-1], t[i-1], x[i], t[i], rep(i) \rangle$  by  $isa[i]$  for  $i \in [0, n)$  to produce an array  $arr$ , where  $arr[i]$  records  $\langle x[sa[i]-1], t[sa[i]-1], x[sa[i]], t[sa[i]], rep(sa[i]) \rangle$ .
- (1c) Initialize  $v = n$ . Scan  $sa, lcp$  and  $arr$  rightward with  $i$  increasing from 0 to  $n-1$ . For each scanned  $\langle sa[i], lcp[i], arr[i] \rangle$ : (1) if  $lcp[i] < v$ , then set  $v = lcp[i]$ ; (2) if  $t[sa[i]-1] = 0$  and  $t[sa[i]] = 1$ , then append

$sa[i]$  and  $v$  to  $sa_{LMS}$  and  $lcp_{LMS}$ , respectively, and reset  $v = n$ .

As can be seen, step 1 determines whether or not a suffix is LMS by checking the types of its preceding and heading characters. To avoid random accesses to  $x$  residing on disks, it first sorts the preceding and heading characters of suffixes by  $isa$  to produce  $arr$ , and then scans  $sa, lcp$  and  $arr$  to identify all the LMS suffixes. During the process, for any two successively found LMS suffixes, say  $suf(sa[i_1])$  and  $suf(sa[i_2])$ , the LCP length of them is calculated by tracing the minimum of  $lcp[i_1 + 1, i_2]$ . After that,  $sa_{LMS}$  and  $lcp_{LMS}$  are checked by using Algorithm 1.

Notice that, when inducing in external memory, the heading characters of successively induced suffixes should be loaded into RAM by sequential I/O operations. For the purpose, the preceding characters calculated by substeps (1a)-(1b) are stored in external memory to facilitate the inducing process in step 2. Specifically, when scanning  $arr$  in substep (1c), we distribute the elements of the array into  $arr_L, arr_S$  and  $arr_{LMS}$  as following: append  $arr[i]$  to  $arr_L$  or  $arr_S$  if  $t[sa[i]] = 0$  or 1, respectively, and append  $arr[i]$  to  $arr_{LMS}$  if  $t[sa[i]-1] = 0$  and  $t[sa[i]] = 1$ .

**Step 2.** This step employs two priority queues  $PQ_L$  and  $PQ_S$  to emulate the RAM-based inducing process in external memory, where each element of both priority queues is a 6-tuple  $\langle ch, ty, ra, pos, lv, rp \rangle$  defined as below:

- $pos$ : starting position of  $suf(pos)$ .
- $ch$ : heading character of  $suf(pos)$ .
- $ty$ : type of  $suf(pos)$ .
- $ra$ : rank of  $suf(pos)$ .
- $lv$ : LCP length of  $suf(pos)$  and its left or right neighbor in the induced SA.
- $rp$ :  $rep(pos)$ .

At the very beginning, step 2 first scans  $sa_{LMS}$  and  $lcp_{LMS}$  to put the sorted LMS suffixes along with the corresponding LCP values into  $PQ_L$  with the sorting key  $\langle ch, ty, ra \rangle$ , then it pops the elements of  $PQ_L$  in ascending order to induce L-type suffixes. Specifically, for each visited element  $e$ , it retrieves the preceding character of  $suf(e.pos)$  from the leftmost unvisited element in  $arr_L$  or  $arr_{LMS}$  if  $e.ty = 0$  or 1, respectively. If the retrieved preceding character is L-type, then it computes the LCP length of  $suf(pos-1)$  and its left neighbor in the induced SA, and puts the induced suffix along with the calculated LCP value into  $PQ_L$ . Meanwhile, it puts  $suf(e.pos)$  into  $PQ_S$  if  $e.ty = 0$ .

When  $PQ_L$  is empty, all the L-type suffixes are sorted in  $PQ_S$  with the sorting key  $\langle ch, ty, ra \rangle$ . Step 2 continues to pop the elements of  $PQ_S$  in descending order to induce S-type suffixes and their LCP values. For each visited element  $e$ , it retrieves the preceding character of  $suf(e.pos)$  from the rightmost unvisited element in  $arr_L$  or  $arr_S$  if  $e.ty = 0$  or 1, respectively. If the preceding character is S-type, then it calculates the LCP length of  $suf(e.pos-1)$  and its right neighbor in the induced SA, and puts the induced suffix along with the calculated LCP value into  $PQ_S$ . Meanwhile, it outputs  $e.pos$  and  $e.lv$  to build the suffix and LCP arrays.

When  $PQ_S$  is empty, the construction of the suffix and LCP arrays is completed and the calculation of the required fingerprints is also finished. Then, step 2 compares the

fingerprints to check the correctness of the induced suffix and LCP arrays.

Notice that, we reuse a technique proposed in [18] to compute the LCP value of two neighboring suffixes in a sub-bucket according to Properties 1-2. Specifically, we record the heading characters and the LCP value of two suffixes from which most recently induce a suffix into  $sa\_bkt(c)$ , for all  $c \in \Sigma$ . Given that  $\Sigma$  is of a constant size, it takes overall  $\mathcal{O}(n)$  time to keep the data structure up-to-date. Besides, for the rightmost L-type and the leftmost S-type/LMS suffixes in a bucket, we compare the repetition counts of their heading characters to compute the LCP length of them.

**Step 3.** This step performs a scan on  $sa$  and  $lcp$  to compare the elements of them with those of the induced suffix and LCP arrays.

### 3.6 Analysis

Clearly, Algorithm 3 can be implemented within sorting complexity in external memory. The space bottleneck of the algorithm occurs when inducing suffixes during the second step. Suppose we respectively use  $a$  and  $b$  words to represent an input character and its type, then it takes at most  $(3a + 3b)n$  words for storing  $arr_L$ ,  $arr_S$  and  $arr_{LMS}$  and  $(4 + a + b)n$  words for sorting elements in  $PQ_L/PQ_S$ .

## 4 EXPERIMENTS

We implement the prototypes of Algorithms 1 and 3 in external memory. Our programs for the algorithms are compiled by gcc/g++ 4.8.4 with -O3 options under ubuntu 14.04 64-bit operating system running on a desktop computer, which is equipped with an Intel Xeon E3-1220 V2 CPU, 4GiB RAM and 500GiB HD. The following metrics normalized by the input's size are investigated for performance evaluation on the real-world datasets listed in Table 1:

- Running time: the running time in microseconds.
- Peak disk use: the peak use of external memory in bytes.
- I/O volume: the number of bytes read from and written to external memory.

### 4.1 Results

Some implementation choices in our programs are as follows. First, we use the second approach in Section 2.4 to facilitate the computation of fingerprints in Algorithm 1. Second, we employ the external-memory containers (vector, sorter and priority queue) provided by the STXXL library [28] to perform scans and sorts on disks. Finally, we use a 32-bit integer to represent each fingerprint and a 40-bit integer to represent each element in the suffix/LCP arrays.

For description convenience, we denote the programs for Algorithms 1 and 3 by ProgA and ProgB, respectively. As shown in Figure 1, ProgA runs faster than ProgB on "enwiki", "uniprot" and "proteins" by about 20 percent. The speed gap between them is mainly due to the difference in their I/O efficiencies. Specifically, the I/O volume of ProgB is  $190n$  in average, while that of ProgA is kept at  $155n$  for different corpora. Notice that, although Algorithm 3 reuses

Algorithm 1 to check  $sa_{LMS}$  and  $lcp_{LMS}$ , the consumption for the verification of  $sa_{LMS}$  and  $lcp_{LMS}$  in ProgB is at most half of ProgA because the number of LMS suffixes is no more than  $\frac{1}{2}n$ . It can be also observed that both programs are insensitive to the input corpus in terms of the space requirement. In details, the peak disk uses of ProgA and ProgB are respectively  $26n$  and  $40n$  on the three corpora.

We also investigate the performance trend of the two programs on the prefix of "enwiki" with the length varying on  $\{1, 2, 4, 8\}$  GiB. Figure 2 illustrates that, as the prefix length increases, a performance degradation occurs to ProgB in both time and I/O efficiencies, but the fluctuation of ProgA can be ignored.

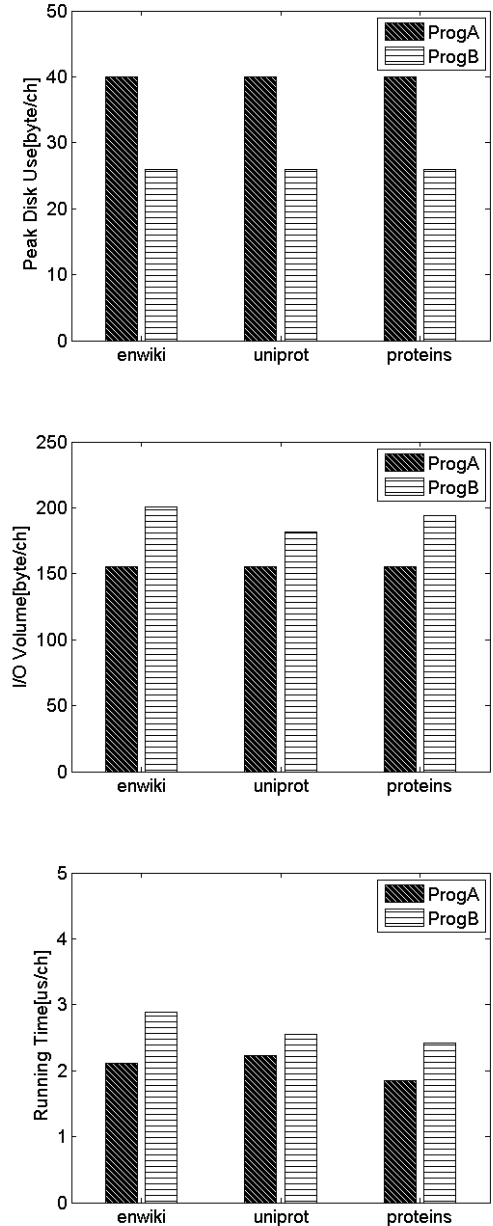


Fig. 1. Experimental results for various corpora.



TABLE 1  
Corpus,  $n$  in Gi, 1 byte per character

Corpora	$n$	$  \Sigma  $	Description
enwiki	8	256	The 8-GiB prefix of an XML dump of English Wikipedia, available at <a href="https://dumps.wikimedia.org/enwiki/">https://dumps.wikimedia.org/enwiki/</a> , dated as 16/05/01.
uniprot	2.5	96	UniProt Knowledgebase, available at <a href="ftp://ftp.expasy.org/databases/.../complete">ftp://ftp.expasy.org/databases/.../complete</a> , dated as 16/05/11.
proteins	1.1	27	Swissprot database, available at <a href="http://pizzachili.dcc.uchile.cl/texts/protein">http://pizzachili.dcc.uchile.cl/texts/protein</a> , dated as 06/12/15.

## 4.2 Discussions

It is identified that both programs heavily rely on the performance of the external memory sorter in use. A potential candidate for improving their speed is to adapt a GPU-based multi-way sorter (e.g., [29], [30]) for sorting massive data using external memory. By the aid of these fast sorting algorithms, the throughputs of the programs are expected to nearly approach the I/O bandwidth. Besides, the first two steps of Algorithm 1 are independent of each other and thus can be executed in parallel for acceleration. This technique can be also applied to check the suffix and LCP arrays of the LMS suffixes in Algorithm 3.

Currently, for Algorithm 3, step 2 constitutes the space bottleneck. It is worthy of mentioning that this step produces a copy of the suffix and LCP array during the inducing and checking processes. Actually, given that  $\Sigma$  is of a constant size and  $sa/lcp$  are known already, we can simply scan the input  $sa/lcp$  to perform the inducing process and compare each induced suffix/LCP value with that in the given  $sa/lcp$  to perform the checking process, resulting in less space consumption. To the end, we must maintain a read pointer for each suffix/LCP bucket in  $sa/lcp$  to scan elements in sequence.

## 5 CONCLUSIONS

We present two probabilistic methods for checking the suffix and LCP arrays in external memory using the Karp-Rabin fingerprinting function. Both methods can be employed to verify the suffix and LCP arrays after their construction, while the second method can be also integrated into an induced-sorting LACA to perform construction and verification in the same time.

We also design the algorithms for these two methods and implement the programs for performance evaluation. An experimental study is conducted to evaluate the time, space and I/O efficiencies. The results indicate that the program for the first method outperforms that for the second method in the running time and I/O volume by about 20 percent, while the peak disk use of the latter is about  $26/40 = 0.65$  as that of the former. There are still quite some opportunities to improve our algorithms and programs for better performance, for this our work has been undergoing.

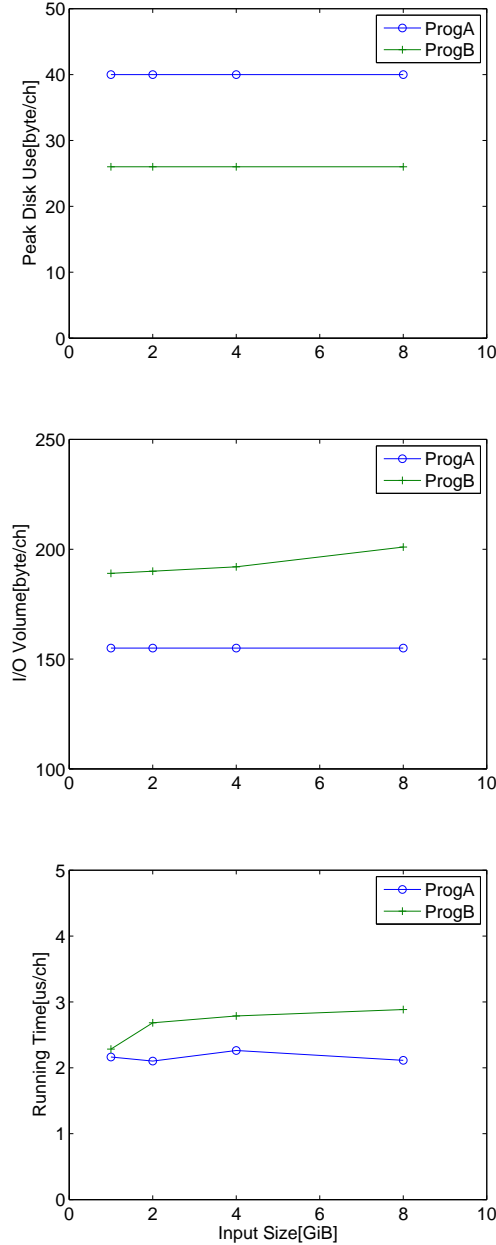


Fig. 2. Experimental results for prefixes of "enwiki".

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