Internal Longest Palindrome Queries
in Optimal Time

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Abstract. Palindromes are strings that read the same forward and backward. Problems of computing palindromic structures in strings have been studied for many years with a motivation of their application to biology. The longest palindrome problem is one of the most important and classical problems regarding palindromic structures, that is, to compute the longest palindrome appearing in a string $T$ of length $n$. The problem can be solved in $O(n)$ time by the famous algorithm of Manacher [Journal of the ACM, 1975]. In this paper, we consider the problem in the internal model. The internal longest palindrome query is, given a substring $T[i..j]$ of $T$ as a query, to compute the longest palindrome appearing in $T[i..j]$. The best known data structure for this problem is the one proposed by Amir et al. [Algorithmica, 2020], which can answer any query in $O(\log n)$ time. In this paper, we propose a linear-size data structure that can answer any internal longest palindrome query in constant time. Also, given the input string $T$, our data structure can be constructed in $O(n)$ time.

Keywords: String algorithms · Palindromes · Internal queries

1 Introduction

Palindromes are strings that read the same backward as forward. Palindromes have been widely studied with the motivation of their application to biology. Computing and counting palindromes in a string are fundamental tasks. Manacher [25] proposed an $O(n)$-time algorithm that computes all maximal palindromes in the string of length $n$. Droubay et al. [16] showed that any string of length $n$ contains at most $n+1$ distinct palindromes (including the empty string). Then, Groult et al. [21] proposed an $O(n)$-time algorithm to enumerate distinct

* Partially supported by JSPS KAKENHI Grant Numbers JP20H05964
palindromes in a string. The above $O(n)$-time algorithms are time-optimal since reading the input string of length $n$ takes $\Omega(n)$ time.

Regarding longest palindrome computation, Funakoshi et al. [18] considered the problem of computing the longest palindromic substring of the string $T'$ after a single character insertion, deletion, or substitution is applied to the input string $T$ of length $n$. Of course, using $O(n)$ time, we can obtain the longest palindromic substring of $T'$ from scratch. The idea is too naïve and looks inefficient. To avoid such inefficiency, Funakoshi et al. proposed an $O(n)$-space data structure that can compute the solution for any editing operation given as a query in $O(\log(\min\{\sigma, \log n\}))$ time where $\sigma$ is the alphabet size. Amir et al. [7] considered the dynamic longest palindromic substring problem, which is an extension of Funakoshi et al.’s problem where up to $O(n)$ sequential editing operations are allowed. They proposed an algorithm that solves this problem in $O(\sqrt{n} \log^2 n)$ time per a single character edit w.h.p. with a data structure of size $O(n \log n)$, which can be constructed in $O(n \log^2 n)$ time. Furthermore, Amir and Boneh [6] proposed an algorithm running in poly-logarithmic time per a single character substitution.

Internal queries are queries about substrings of the input string $T$. Let us consider a situation where we solve certain problem for each of $k$ different substrings of $T$. If we run an $O(|w|)$-time algorithm from scratch for each substring $w$, the total time complexity can be as large as $O(kn)$. Therefore, by performing appropriate preprocessing on $T$, we construct some data structure for the query to output each solution efficiently. Such efficient data structures for palindromic problems are known. Rubinchik and Shur [29] proposed an algorithm that computes the number of distinct palindromes in a given substring of an input string of length $n$. Their algorithm runs in $O(\log n)$ time with a data structure of size $O(n \log n)$, which can be constructed in $O(n \log n)$ time. Amir et al. [7] considered a problem of computing the longest palindromic substring in a given substring of the input string of length $n$; it is called the internal longest palindrome query. Their algorithm runs in $O(\log n)$ time with a data structure of size $O(n \log n)$, which can be constructed in $O(n \log^2 n)$ time.

This paper proposes a new algorithm for the internal longest palindrome query. The algorithm of Amir et al. [7] uses 2-dimensional orthogonal range maximum queries [3,4,12]; furthermore, time and space complexities of their algorithm are dominated by this query. Instead of 2-dimensional orthogonal range maximum queries, by using palindromic trees [30], weighted ancestor queries [19], and range maximum queries [17], we obtain a time-optimal algorithm.

**Theorem 1.** Given a string $T$ of length $n$ over a linearly sortable alphabet, we can construct a data structure of size $O(n)$ in $O(n)$ time that can answer any internal longest palindrome query in $O(1)$ time.

Here, an alphabet is said to be linearly sortable if any sequence of $n$ characters from $\Sigma$ can be sorted in $O(n)$ time. For example, integer alphabet $\{1, 2, \ldots, nc\}$ for some constant $c$ is linearly sortable because we can sort a sequence from the alphabet in linear time by using a radix sort with base $n$. 
Related Work. Internal queries have been studied on many problems not only those related to palindromic structures. For instance, Kociumaka et al. [24] considered the internal pattern matching queries that are ones for computing the occurrences of a substring $U$ of the input string $T$ in another substring $V$ of $T$. Besides, internal queries for string alignment [33, 11, 13, 12, 2, 1], longest common prefix $[5, 12, 19]$, and longest common substring $[7]$ have been studied in the last two decades. See [23] for an overview of internal queries. We also refer to [10, 22, 15, 14, 2, 11] and references therein.

2 Preliminaries

2.1 Strings and Palindromes

Let $\Sigma$ be an alphabet. An element of $\Sigma$ is called a character, and an element of $\Sigma^*$ is called a string. The empty string $\varepsilon$ is the string of length 0. The length of a string $T$ is denoted by $|T|$. For each $i$ with $1 \leq i \leq |T|$, the $i$-th character of $T$ is denoted by $T[i]$. For each $i$ and $j$ with $1 \leq i, j \leq |T|$, the string $T[i]T[i+1] \cdots T[j]$ is denoted by $T[i..j]$. For convenience, let $T[i..j] = \varepsilon$ if $i > j$. If $T = xyz$, then $x$, $y$, and $z$ are called a prefix, substring, and suffix of $T$, respectively. The string $y$ is called an infix of $T$ if $x \neq \varepsilon$ and $z \neq \varepsilon$. The reversal of string $T$ is denoted by $T^R$, i.e., $T^R = T[|T|] \cdots T[2]T[1]$. A string $T$ is called a palindrome if $T = T^R$. Note that $\varepsilon$ is also a palindrome. For a palindromic substring $T[i..j]$ of $T$, the center of $T[i..j]$ is $\frac{i+j}{2}$. A palindromic substring $T[i..j]$ is called a maximal palindrome in $T$ if $i = 1$, $j = |T|$, or $T[i−1] \neq T[j+1]$. In what follows, we consider an arbitrary fixed string $T$ of length $n > 0$. In this paper, we assume that the alphabet $\Sigma$ is linearly sortable. We also assume the word-RAM model with word size $\omega \geq \log n$ bits.

Let $z$ be the number of palindromic suffixes of $T$. Also, let $suf(T) = (s_1, s_2, \ldots, s_z)$ be the sequence of the lengths of palindromic suffixes of $T$ sorted in increasing order. Further let $dif_i = s_i - s_{i−1}$ for each $i$ with $2 \leq i \leq z$. For convenience, let $dif_1 = 0$. Then, the sequence $(dif_1, \ldots, dif_z)$ is monotonically non-decreasing [26]. Let $(suf_1, suf_2, \ldots, suf_p)$ be the partition of $suf(T)$ such that for any two elements $s_i, s_j$ in $suf(T)$, $s_i, s_j \in suf_k$ for some $k$ iff $dif_i = dif_j$. By the definition, each $suf_k$ forms an arithmetic progression. It is known that the number $p$ of arithmetic progressions satisfies $p \in \mathcal{O}(\log n)$ [26]. For $1 \leq k \leq p$ and $1 \leq \ell \leq |suf_k|$, $suf_{k, \ell}$ denote the $\ell$-th term of $suf_k$. Fig. 1 shows an example of the above definitions.

2.2 Tools

In this section, we list some data structures used in our algorithm in Section 3.

Palindromic Trees and Series Trees. The palindromic tree of $T$ is a data structure that represents all distinct palindromes in $T$ [30]. Let $paltree(T)$ denote the
Theorem 2 ([30]). Given a string $T$ over a linearly sortable alphabet, the palindromic tree of $T$, including its suffix links and series links, can be constructed in $O(n)$ time. Also, LSufPal can be computed in $O(n)$ time.

Let us consider the sub-graph $S$ of paltree($T$) that consists of all ordinary nodes and reversals of all series links. By the definition, $S$ has no cycle and $S$
is connected (any node is reachable from the node ε), i.e., it forms a tree. We call the tree S the series tree of T, and denote it by 

\[ \text{seriestree}(T) \]

By definition of series links, the set of lengths of palindromic suffixes of v that are longer than \(|\text{serieslink}(v)|\) can be represented by an arithmetic progression. Each node v stores the arithmetic progression, represented by a triple consisting of its first term, its common difference, and the number of terms. Arithmetic progressions for all nodes can be computed in linear time by traversing the palindromic tree.

It is known that the length of a path consisting of series links is \(O(\log n)\) \[30\]. Hence, the height of \(\text{seriestree}(T)\) is \(O(\log n)\). See the right part of Fig. 2 for illustration.

**Weighted Ancestor Query.** A rooted tree whose nodes are associated with integer weights is called a monotone-weighted-tree if the weight of every non-root node is not smaller than the parent’s weight. Given a monotone-weighted-tree T for preprocess and a node v and an integer k for query, a weighted ancestor query (WAQ) returns the highest ancestor u of v such that the weight of u is greater than k. Let \(\text{WAQ}_T(v, k)\) be the output of the weighted ancestor query for tree T, node v, and integer k. See Fig. 3 for concrete examples. It is known that there is an \(O(N)\)-space data structure that can answer any weighted ancestor query in \(O(\log \log N)\) time where \(N\) is the number of nodes in the tree \[3\]. In general, the query time \(O(\log \log N)\) is known to be optimal within \(O(N)\) space \[28\]. On
monotone-weighted-tree $T$

Fig. 3: Illustration for weighted ancestor query. Integers in nodes denote the weights. Given a node $v_5$ in a monotone-weighted-tree $T$ and an integer $k = 6$ for query, WAQ returns the node $v_3$ since $v_3$ is an ancestor of $v_5$, weight($v_3$) > $k = 6$, and the weight of the parent $v_2$ of $v_3$ is not greater than $k = 6$.

the other hand, if the height of the input tree is low enough, the query time can be improved:

**Theorem 3 (Proposition 18 in [19]).** Let $\omega$ be the word size. Given a monotone-weighted-tree with $N$ nodes and height $O(w)$, one can construct an $O(N\omega)$-bits data structure in $O(N)$ time that can answer any weighted ancestor query in constant time.

In this paper, we use weighted ancestor queries only on the series tree of $T$ whose height is $O(\log n) \subseteq O(\omega)$, thus we will apply Theorem 3.

**Range Maximum Query.** Given an integer array $A$ of length $m$ for preprocess and two indices $i$ and $j$ with $1 \leq i \leq j \leq m$ for query, range maximum query returns the index of a maximum element in the sub-array $A[i..j]$. Let $\text{RMQ}_A(i,j)$ be the output of the range maximum query for array $A$ and indices $i,j$. In other words, $\text{RMQ}_A(i,j) = \arg \max_k \{A[k] \mid i \leq k \leq j\}$. The following result is known:

**Theorem 4 ([17]).** Let $m$ be the size of the input array $A$. There is a data structure of size $2m + o(m)$ bits that can answer any range maximum query on $A$ in constant time. The data structure can be constructed in $O(m)$ time.

### 3 Internal Longest Palindrome Queries

In this section, we propose an efficient data structure for the internal longest palindrome query defined as follows:
Internal longest palindrome query

Preprocess: A string $T$ of length $n$.
Query input: Two indices $i$ and $j$ with $1 \leq i \leq j \leq n$.
Query output: The longest palindromic substring in $T[i..j]$.

Our data structure requires only $O(n)$ words of space, and can answer any internal longest palindrome query in constant time. To answer queries efficiently, we classify all palindromic substrings of $T$ into palindromic prefixes, palindromic infixes, and palindromic suffixes. First, we compute the longest palindromic prefix and the longest palindromic suffix of $T[i..j]$. Second, we compute a palindromic infix that is a candidate for the answer. As we will discuss in a later subsection, this candidate may not be the longest palindromic infix of $T[i..j]$. Finally, we compare the three above palindromes and output the longest one.

3.1 Palindromic Suffixes and Prefixes

We compute the longest palindromic suffix of $T[i..j]$ using the fact that the set of lengths of palindromic suffixes can be represented by $O(\log n)$ arithmetic progressions.

In the preprocessing, we build $\text{seriestree}(T)$ and a data structure for the weighted ancestor queries on $\text{seriestree}(T)$, and compute $\text{LSufPal}$ as well. The query algorithm consists of three steps:

Step 1: Obtain the longest palindromic suffix of $T[1..j]$.
We obtain the longest palindromic suffix $v$ of $T[1..j]$ from $\text{LSufPal}[j]$. If $|v| \leq |T[i..j]|$, then $v$ is the longest palindromic suffix of $T[i..j]$. Then we return $T[j - |v| + 1..j]$ and the algorithm terminates. Otherwise, we continue to Step 2.

Step 2: Determine the group to which the desired length belongs.
Let $\ell$ be the length of the longest palindromic suffix of $T[i..j]$ we want to know. First, we find the shortest palindrome $u$ that is an ancestor of $v$ in $\text{seriestree}(T)$ and has length at least $|T[i..j]|$. Such palindrome (equivalently the node) $u$ can be found by weighted ancestor query on the series tree, i.e., $u = \text{WAQ}_{\text{seriestree}(T)}(v, j - i)$. Then $|u|$ is an upper bound of $\ell$. Let $\text{suf}_\alpha$ be the group such that $|u| \in \text{suf}_\alpha$. If the smallest element $\text{suf}_{\alpha,1}$ in $\text{suf}_\alpha$ is at most $|T[i..j]|$, the length $\ell$ belongs to the same group $\text{suf}_\alpha$ as $|u|$. Otherwise, the length $\ell$ belongs to the previous group $\text{suf}_{\alpha-1}$.

Step 3: Calculate the desired length.
Let $\text{suf}_\beta$ be the group to which the length $\ell$ belongs, which is determined in Step 2. Since $\text{suf}_\beta$ is an arithmetic progression, the desired length $\ell$ can be computed by performing a constant number of arithmetic operations. Then we return $T[j - \ell + 1..j]$.

See Fig. 4 for illustration. Now, we show the correctness of the algorithm and analyze time and space complexities.
Fig. 4: Illustration for how to compute the longest palindromic suffix of $T[i..j]$. The graph on the right hand depicts a part of the series tree of a string $T$, and the lengths of palindromes are written inside the nodes. In Step 1, we obtain the length $suf_{5,1}$ of the longest palindromic suffix $v_1$ of $T[1..j]$. In Step 2, we find $suf_{3,3}$ by $\text{WAQ}_{\text{series}T}(v_1, j - i)$. Since $suf_{3,1} > j - i + 1$, the desired length belongs to $suf_3$. In Step 3, since $suf_{3,3}$ is an arithmetic progression, we can find that $suf_{3,1}$ is the longest palindromic suffix of $T[i..j]$ in constant time.

**Lemma 1.** We can compute the longest palindromic suffix and prefix of $T[i..j]$ in $O(1)$ time with a data structure of size $O(n)$ that can be constructed in $O(n)$ time.

**Proof.** In the preprocessing, we build $\text{series}T$ and a data structure of weighted ancestor query on $\text{series}T$ in $O(n)$ time (Theorem 2 and 3). Recall that since the height of $\text{series}T$ is $O(\log n) \subseteq O(\omega)$, we can apply Theorem 3 to the series tree. Again, by Theorem 2 and 3, the space complexity is $O(n)$ words of space.

In what follows, let $\ell$ be the length of the longest palindromic suffix of $T[i..j]$. In Step 1, we can obtain the longest palindromic suffix $v$ of $T[1..j]$ by just referring to $\text{LSufPal}[j]$. If $|v| \leq |T[i..j]|$, $v$ is also the longest palindromic suffix of $T[i..j]$, i.e., $\ell = |v|$. Otherwise, $v$ is not a substring of $T[i..j]$. In Step 2, we first query $\text{WAQ}_{\text{series}T}(v, j - i)$. The resulting node $u$ corresponds to a palindromic suffix of $T[1..j]$, which is longer than $|T[i..j]|$. Let $suf_\alpha$ and $suf_\beta$ be the groups to which $|u|$ and $\ell$ belongs, respectively. If the smallest element $suf_{\alpha,1}$ in $suf_\alpha$ is at most $j - i + 1$, then the desired length $\ell$ satisfies $suf_{\alpha,1} \leq \ell \leq |u|$. Namely, $\beta = \alpha$. Otherwise, if $s$ is greater than $j - i + 1$, $\ell$ is not in $suf_\alpha$ but is in $suf_{\alpha-x}$ for some $x > 1$. If we assume that $\ell$ belongs to $suf_{\alpha-y}$ for some $y \geq 2$, the length of $\text{series}link(u)$ belonging to $suf_{\alpha-y}$ is longer than $T[i..j]$. However, it
contradicts that \( u \) is the answer of \( \text{WAQ}_{\text{seriestree}}(T, j - i) \). Hence, if \( s \) is greater than \( j - i + 1 \), then the length \( \ell \) is in \( \text{sup}_{\alpha-1} \). Namely, \( \beta = \alpha - 1 \). In Step 3, we can compute \( \ell \) in constant time since we know the arithmetic progression \( \text{sup}_\beta \) to which \( \ell \) belongs. More specifically, \( \ell \) is the largest element that is in \( \text{sup}_\beta \) and is at most \( j - i + 1 \).

Throughout the query algorithm, all operations, including \( \text{WAQ} \) and operations on arithmetic progressions, can be done in constant time. Thus the query algorithm runs in constant time. \( \square \)

### 3.2 Palindromic Infixes

Next, we compute the longest palindromic infix except for ones that are obviously shorter than the longest palindromic prefix or the longest palindromic suffix of the query substring. We show that to find the desired palindromic infix, it suffices to consider maximal palindromes whose centers are between the centers of the longest palindromic prefix and the longest palindromic suffix of \( T[i..j] \). Let \( t \) be the ending position the longest palindromic prefix and \( s \) be the starting position of the longest palindromic suffix. Namely, \( T[i..t] \) is the longest palindromic prefix and \( T[s..j] \) is the longest palindromic suffix of \( T[i..j] \).

**Lemma 2.** Let \( w \) be a palindromic substring of \( T[i..j] \) and \( c \) be the center of \( w \). If \( c < \frac{i + t}{2} \) or \( c > \frac{s + j}{2} \), \( w \) cannot be the longest palindromic substring of \( T[i..j] \).

*Proof.* Let \( w = T[p..q] \). We focus only on the case where \( c < \frac{i + t}{2} \) here since the other case, \( c > \frac{s + j}{2} \), can be treated symmetrically. Since \( i \leq p \) and \( c < \frac{i + t}{2} \) hold, \(|w| = 2(c - p) + 1 < 2(\frac{i + t}{2} - i) + 1 = t - i + 1 = |T[i..t]| \). Namely, \( w \) is shorter than the longest palindromic prefix of \( T[i..j] \) (see also Fig. 5). Thus, \( w \) cannot be the longest palindromic substring of \( T[i..j] \). \( \square \)

**Lemma 3.** Let \( w \) be a palindromic substring of \( T \) and \( c \) be the center of \( w \). If \( \frac{i + t}{2} < c < \frac{s + j}{2} \), then \( w \) is a palindromic infix of \( T[i..j] \).

*Proof.* Let \( w = T[p..q] \). Then, \( c = \frac{p + q}{2} \). To prove that \( w \) is a palindromic infix, we show that \( p > i \) and \( q < j \). For the sake of contradiction, we assume \( p \leq i \). If \( \frac{i + t}{2} < c < \frac{s + j}{2} \), there exists a palindromic prefix whose center is \( c \) and the length is \( 2(c - i) + 1 = 2c - 2i + 1 > (i + t) - 2i + 1 = t - i + 1 = |T[i..t]| \). However, this contradicts that \( T[i..t] \) is the longest palindromic prefix of \( T[i..j] \) (see also Fig. 6). Otherwise, if \( \frac{i + t}{2} < c < \frac{s + j}{2} \), there exists a palindromic suffix whose center is \( c \) and the length is \( 2(j - c) + 1 = 2j - 2c + 1 > 2j - (s + j) + 1 = j - s + 1 = |T[s..j]| \). However, this contradicts that \( T[s..j] \) is the longest palindromic suffix of \( T[i..j] \) (see also Fig. 6). Therefore, \( p > i \). We can show \( q < j \) in a symmetric way. \( \square \)

By Lemmas 2 and 3, when a palindromic infix \( w \) of \( T[i..j] \) is the longest palindromic substring of \( T[i..j] \), the center of \( w \) must be locate between \( \frac{i + t}{2} \) and \( \frac{s + j}{2} \). Furthermore, \( w \) is a maximal palindrome in \( T \). In other words, \( w \) is the
longest maximal palindrome in $T$ whose center $c$ satisfies $\frac{i+t}{2} < c < \frac{s+j}{2}$. To find such a (maximal) palindrome, we build a succinct RMQ data structure on the length-$(2n-1)$ array $MP$ that stores the lengths of maximal palindromes in $T$. For each integer and half-integer $c \in \{1, 1.5, \ldots, n - 0.5, n\}$, $MP[2c-1]$ stores the length of the maximal palindrome whose center is $c$. By doing so, when the indices $t$ and $s$ are given, we can find a candidate for the longest palindromic substring which is an infix of $T[i..j]$ in constant time. More precisely, the length of the candidate is $MP[RMQ_{mp}(i+t, s+j-2)]$ since the center $c$ of the candidate satisfies $\frac{i+t}{2} < c < \frac{s+j}{2}$ ($i + t - 1 < 2c - 1 < s + j - 1$). By Manacher’s algorithm [25], $MP$ can be constructed in $O(n)$ time.

To summarize, we have shown our main theorem:
Theorem 1. Given a string $T$ of length $n$ over a linearly sortable alphabet, we can construct a data structure of size $O(n)$ in $O(n)$ time that can answer any internal longest palindrome query in $O(1)$ time.

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