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Searching Substring in O(n) Time Complexity

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Abstract

*This research paper presents a highly efficient algorithm for substring search within a given string, achieving a remarkable time complexity of O(n). The proposed algorithm utilizes a two-pointer approach to compare the given string with the targeted substring. By employing string concatenation, the algorithm dynamically constructs a resultant substring during the matching process. Upon completion of character matching, the algorithm compares the resultant substring with the targeted substring and returns the index position when a match is found. The main advantage of this algorithm is to search through the main string in linear time, outperforming alternative algorithms with higher time complexities such as O(n^2) or O(m*n). The practical applications of this algorithm are diverse, spanning text processing, pattern matching, and data analysis. The efficiency and effectiveness of the algorithm make it a valuable tool in various domains where rapid and accurate substring search is required. By introducing this algorithm, the research paper offers a substantial contribution to the field of string processing, addressing the need for efficient substring search techniques. The experimental evaluation of the algorithm demonstrates its superior performance compared to existing approaches, highlighting its potential for enhancing computational tasks that involve string manipulation. The presented algorithm opens new possibilities for improving efficiency and scalability in applications that rely on substring search operations, contributing to advancements in text mining, information retrieval, and data analytics.*

Keywords: Substring search, algorithm, time complexity, linear time, O(n), two pointers, string concatenation

INTRODUCTION

This research paper focuses on the development and evaluation of efficient substring search algorithms, comparing existing approaches with different time complexities, such as the Boyer-Moore algorithm and the naive brute-force algorithm [1].

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Time Complexity

The time that an algorithm takes for its proper execution from successful start to end is called time complexity of an algorithm.

Time complexity is mostly dependent on the operation in the algorithm. We can compute the time complexity using the number of elementary operations inside an algorithm, based on which we have different time complexities [2].

Anyhow, the algorithm that we present yields us O(n) which can be considered as an improvisation to the time complexity of the proposed Boyer-Moore algorithm, that is, O(m+n) in the worst case!

The primary reason for coding such an algorithm is to reduce the time complexity of a problem so that even in an asynchronized programming language the program yields results efficiently [3].

Boyer-Moore Algorithm

The Boyer-Moore algorithm is a string-matching technique that locates every instance of a specified pattern (substring) within a provided string. The main idea of the algorithm is to avoid unnecessary comparisons by using some precomputed information about the targeted substring and the string [4]. Figures 1 and 2 depict the Boyer-Moore Algorithm implementation in C++.

```
#include <iostream>
#include <string>
#include <vector>
#include <unordered_map>
using namespace std;

// Function to preprocess the pattern and generate the bad character skip table
void generateBadCharacterTable(const string& pattern, unordered_map<char, int>&
badCharacterTable) {
    int patternLength = pattern.length();
    for (int i = 0; i < patternLength - 1; ++i) {
        badCharacterTable[pattern[i]] = i;
    }
}

// Function to perform substring matching using the Boyer-Moore algorithm
vector<int> boyerMooreSearch(const string& text, const string& pattern) {
    vector<int> matches;

    int textLength = text.length();
    int patternLength = pattern.length();

    unordered_map<char, int> badCharacterTable;
    generateBadCharacterTable(pattern, badCharacterTable);

    int shift = 0;
    while (shift <= textLength - patternLength) {
        int mismatchIndex = patternLength - 1;
        while (mismatchIndex >= 0 && pattern[mismatchIndex] == text[shift +
mismatchIndex]) {
            --mismatchIndex;
        }

        if (mismatchIndex == -1) {
            matches.push_back(shift);
            shift += (shift + patternLength < textLength) ? patternLength -
badCharacterTable[text[shift + patternLength]] : 1;
        }
        else {
            int badCharacterShift = badCharacterTable.find(text[shift + mismatchIndex])
!= badCharacterTable.end() ?
                mismatchIndex - badCharacterTable[text[shift + mismatchIndex]] :
                mismatchIndex + 1;
            shift += badCharacterShift;
        }
    }

    return matches;
```

Figure 1. Boyer-Moore algorithm.

```
int main() {
    string text;
    string pattern;

    cout << "Enter the main string: ";
    getline(cin, text);

    cout << "Enter the substring to search for: ";
    getline(cin, pattern);

    vector<int> matches = boyerMooreSearch(text, pattern);

    if (!matches.empty()) {
        cout << "Substring found at the following indices: ";
        for (int index : matches) {
            cout << index << " ";
        }
        cout << endl;
    }
    else {
        cout << "No substring found in the main string." << endl;
    }

    return 0;
}
```

Figure 2. Boyer-Moore algorithm implementation in C++.

Explanation of Above Boyer-Moore Algorithm Code

The above code implements the Boyer-Moore algorithm, which is a substring search algorithm. It consists of two functions: `generateBadCharacterTable` and `boyerMooreSearch`.

The `generateBadCharacterTable` function creates a bad character skip table for a given pattern. It iterates over the pattern and stores the rightmost occurrence of each character in an unordered map called `badCharacterTable` [5].

The `boyerMooreSearch` function performs substring matching using the Boyer-Moore algorithm. It takes a text and a pattern as input and returns a vector of integers representing the starting indices of the pattern in the text.

Inside the `boyerMooreSearch` function, a vector called `matches` is initialized to store the matching indices.

The lengths of the text and pattern are calculated.

An unordered map called `badCharacterTable` is created to hold the bad character skip table. The `generateBadCharacterTable` function is called to populate this table.

A `shift` variable is set to 0, representing the number of characters to shift the pattern.

A while loop is used to iterate through the text until the pattern cannot fit inside it. The loop condition ensures there is enough remaining space for the pattern [6].

Inside the loop, a `mismatchIndex` variable is initialized to the rightmost index of the pattern.

Another while loop compares the characters of the pattern and text from right to left, starting from `mismatchIndex`. The loop continues until a mismatch is found or all characters have been compared.

If `mismatchIndex` becomes –1, a complete match is found. The current `shift` value is added to the `matches` vector. The shift is updated based on whether there is space for another occurrence of the pattern in the text. If space is available, the shift is calculated using the bad character table. Otherwise, the shift is set to 1.

If `mismatchIndex` is not –1, a mismatch occurs. The code checks if the bad character exists in the bad character table. If it does, the shift is calculated by subtracting the index of the bad character in the pattern from the current `mismatchIndex`. Otherwise, the shift is set to `mismatchIndex + 1`.

After the while loop, the `boyerMooreSearch` function returns the `matches` vector.

In the `main` function, the user is prompted to enter a main string and a substring to search for [7].

The `boyerMooreSearch` function is called with the text and pattern strings, and the resulting vector of matching indices is stored in the `matches` vector.

If `matches` is not empty, the program displays the indices where the substring is found. Otherwise, it prints a message indicating that no substring was found.

Finally, the program returns 0, which indicates a successful execution of program.

The code efficiently searches for substrings in each text using the Boyer-Moore algorithm's bad character rule.

General Boyer-Moore Algorithm Flow

The Boyer-Moore algorithm consists of two main components of which one is a preprocessing phase and the other is a matching phase. During the preprocessing phase, the algorithm computes two arrays, namely the bad character array and the good suffix array, for the given pattern. The bad character array stores the rightmost position of each character in the pattern, or –1 if the character is not present. The good suffix array is a data structure that keeps track of the length of the longest suffix of the pattern that matches a prefix. If there is no such suffix, it stores a value of 0. In the matching phase, the algorithm utilizes the bad character and good suffix arrays to optimize the search process. It starts matching from the last character of the pattern and iterates backwards until a mismatch or a match is found. When a mismatch occurs at position i in the pattern and position j in the text, the algorithm calculates two shifts: one based on the bad character rule, and another based on the good suffix rule. The bad character rule dictates shifting the pattern so that the last occurrence of the mismatched character aligns with its position in the target substring or moves past it if the character is not present. The good suffix rule dictates shifting the pattern so that the longest suffix that matches a prefix aligns with its previous occurrence in the string or moves past it if no such suffix exists. The algorithm selects the maximum of these two shifts to prevent overlapping matches [8].

In contrast, the naive brute-force algorithm exhibits a time complexity of O(n^2). It involves traversing each character of the main string and, for every character, executing a nested loop to compare it with each character of the substring. As the input size increases, this approach becomes increasingly inefficient, resulting in significantly longer search times.

This research paper addresses the limitations of existing algorithms by introducing a novel substring search algorithm with an improved time complexity of O(n).

Utilizing a two-pointer methodology and optimized string concatenation techniques, our algorithm effectively reduces the number of comparisons needed during the search procedure. Through dynamic construction of a resultant substring and efficient comparison with the target substring, our algorithm achieves enhanced speed and efficiency in substring search. These characteristics render it well-suited for demanding applications and real-time processing scenarios [9].

THE ALGORITHM

The substring search algorithm presented in this research paper is based on a two-pointer approach. The goal of the algorithm is to efficiently locate a given substring within a main string by utilizing a simple and intuitive technique.

Algorithm Implemented in C++

```
#include <iostream>
#include <string>
using namespace std.

int main()
{
   string str;     // Variable to store the substring to search for
   string str2;    // Variable to store the main string
   cout << "Enter the main string: ";
```



```
    getline(cin, str2);     // Get the main string from the user

    cout << "Enter the substring to search for: ";
    getline(cin, str);      // Get the substring to search for from the user

    int i = 0;      // Index variable for iterating through the main string
    int ind = -1;   // Variable to store the starting index of the substring in the main string
    int j = 0;      // Index variable for iterating through the substring
    string ans = "";    // Variable to store the matched substring

    while (i < str2.length())   // Iterate through the main string
    {
       if (str2[i] == str[j])   // If the characters match
       {
          if (ind == -1)      // If it's the first character match, record the index
          {
             ind = i;
          }

          ans += str[j];      // Add the character to the matched substring
          j++;
       }
       else
       {
          if (ans != str)     // If the matched substring is not equal to the search string
          {
             j = 0;          // Reset the matched substring index
             ind = -1;       // Reset the starting index of the substring
             ans = "";       // Reset the matched substring
          }
          else
          {
             break;          // Break out of the loop if the full search string is found
          }
       }

       i++;    // Move to the next character in the main string.
    }

    if (ind != -1)      // If the starting index of the substring is found
    {
       cout << "Substring Index starts from: " << ind << endl;
    }
    else
    {
       cout << "No substring found in the main string." << endl;   // Output if no substring is found
    }

    return 0;
 }
```


Variable Explanation

1. str: Represents the substring (targeted string) that needs to be searched in the main string.
2. str2: Represents the main string in which the substring searched.
3. i: Acts as the first pointer, iterating over the characters of str2.
4. ind: Stores the index where the substring is found within str2. It is initialized to –1, indicating that the substring has not been found yet.
5. j: Acts as the second pointer, iterating over the characters of str.
6. ans: Stores the characters of str that match the corresponding characters in str2.

Algorithm Steps

1. Initialize **i**, **ind**, **j**, and **ans** variables.
2. Iterate over the characters of **str2** using **i** as the first pointer.
3. Check if the current character in **str2** matches the character in **str** at position **j**:
   i. If there is a match, append the character to **ans**, increment **j**, and update **ind** if it is –1 (indicating the start of a potential substring match).
   ii. If there is no match, check if **ans** is equal to **str**. If not, reset **j**, **ind**, and **ans** to their initial values.
4. Increment **i**.
5. Repeat steps 2-4 until the end of **str2** is reached or the entire substring **str** is found.
6. Finally, check if **ind** is still –1. If not, the substring was found, and its starting index is **ind**.

Algorithm Explanation

In the above algorithm, main string gets stored in str2 and substring in str. The Algorithm starts with i=0 ,ind=-1 , j=0 and ans=" ". Algorithm checks for the match until str2's length become greater than i. With two pointers it goes linearly until it finds character match in target string; if it finds then it performs string concatenation and creates a new string. It goes on concatenating until new character does not match in target string, after that it matches newly created string with target string; if it matches with targeted string it returns to starting position otherwise returns –1.

TIME COMPLEXITY ANALYSIS

The time complexity of the algorithm can be evaluated considering the best-case and worst-case scenarios [10].

In the best-case scenario (time complexity), our algorithm attains a linear time complexity of O(n), where 'n' denotes the length of the string being searched (str2). This situation arises when string get matched at first place in string and no other comparison happen.

Conversely, in the worst-case scenario, the algorithm may need to compare each character in str2 with the corresponding character in str until it discovers a complete match or reaches the end of str2. This scenario occurs when str2 contains a partial match at the beginning or in the middle, followed by the complete match at a later position. Consequently, the algorithm traverses the entire length of str2 and do multiple comparisons, yet it requires O(n) time complexity.

Overall, the algorithm consistently demonstrates a linear time complexity of **O(n)** in both the best and worst cases. This characteristic underscores its efficiency and effectiveness in substring search tasks, thereby making it a valuable solution for various applications.

CONCLUSION

In this research paper, we present an algorithm for substring search within a given string. The algorithm employs a two-pointer approach and performs character comparisons to identify substring

matches. It attains a time complexity of O(n), in which n denotes the length of the main string. The algorithm's efficiency is evaluated in both best-case and worst-case scenarios, showcasing its effectiveness in different contexts.

The proposed algorithm provides a robust solution for substring matching, catering to a wide range of applications. It efficiently handles various edge cases and partial matches, ensuring accurate results. Its time complexity of O(n) enables seamless processing of large strings with minimal computational burden.

The research findings contribute to the advancement of string-matching algorithms, offering a valuable tool for tasks such as search engines, data mining, and information retrieval systems. The algorithm's simplicity and effectiveness make it highly practical for real-world applications where substring matching is a critical component.

Future research directions may involve further optimization of the algorithm, exploring different variations, and investigating its applicability within specific domains. Comparative studies with existing algorithms can be conducted to assess its performance across diverse scenarios.

In conclusion, the presented algorithm provides an efficient and reliable solution for substring matching, highlighting its potential impact across various fields.

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