COSC 528 Design and Analysis of Algorithms

Project Title: String Searching Algorithms

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Introduction

The goal of string searching algorithms is to find the location of a specific text pattern within a larger body text. The larger body of text can be described either as a sentence, paragraph, or book. The topic of string searching has greatly influenced the computer science community and plays an important role in solving various real-world problems.

String matching algorithms are commonly used in plagiarism detection, where the documents to be compared are decomposed into string arrays or tokens and are compared with various string-matching algorithms such as Knuth-Morris-Pratt algorithms. String matching algorithms are also widely used in Bioinformatics and DNA Sequencing since these solve the problems of genetic sequences to find DNA patterns. Various string-matching algorithms are collectively used to find the occurrence of the pattern set. String matching algorithms are also widely used in search engines or content search in large databases, where string matching algorithms are used to categorize and organize the data efficiently. Categorization is done using search keywords, thus making it easier for the user to find information they are searching for. Some other common applications of string-matching algorithms are in digital forensics, spelling checker, spam filters, and intrusion detection system. In this paper we focus on two string matching algorithms which are Naïve algorithm for pattern searching (Brute-Force) and Knuth-Morris-Pratt algorithm.

Algorithms

(i) Naïve Pattern Search Algorithm (Brute Force): This algorithm compares the pattern to a text such as sentence. The algorithm compares one character at a time until a match is found. An example of this algorithm in action is shown below:

Characters: TWO ROADS ARE DIVERGED IN A YELLOW WOOD Pattern: ROADS		Pattern Found
Iteration 1		
T	WO ROADS ARE DIVERGED IN A YELLOW WOOD	FALSE
R	OADS	
TW	WO ROADS ARE DIVERGED IN A YELLOW WOOD	FALSE
RO	ADS	
TWO ROA	ROADS ARE DIVERGED IN A YELLOW WOOD DS	FALSE
Iteration 2		
R R	OADS ARE DIVERGED IN A YELLOW WOOD OADS	TRUE

Table 1: Implementation of Naïve Algorithm (Brute Force)

The algorithm can be designed to either be stopped on the first occurrence or upon reaching the end of the text. A pseudo-code for this algorithm is provided below:

```
NaïvePatternSearch(Text, Pattern, m, n)
        m = length(Text)
        n = length(Pattern)
        for( i = 0; i < n – m + 1; i++)
            j = 0
            while (j < m)
                if (Text[ i + j] ≠ Pattern[j])
                    break
                j = j + 1
            if (j == m)
                return(i, i + j – 1)
```

(ii) Knuth-Morris-Pratt Algorithm: Another popular algorithm that is used in pattern searching is called the Knuth-Morris-Pratt (KMP) Algorithm. The KMP algorithm differs from the Naïve pattern searching algorithm (brute-force) by keeping track of information gained from previous comparisons. The algorithm utilizes a preprocessing function that indicates how much of the last comparison can be reused if it fails. The preprocessing function is defined as the longest prefix of a pattern P[0,….,j] that is also a suffix of P[1,….,j]. An example of KMP's preprocessing function is outlined below:

j	0	1	2	3	4	5
P[j]	a	b	a	b	a	c
f(j)	0	0	1	2	3	0

Table 2: Implementation of Knuth-Morris-Pratt Algorithm's preprocessing function

If we look at table 2, we can see how much of the beginning of a string matches up with the portion immediately preceding a failed comparison. We notice that if a comparison fails at say j = 4 then we know that a and b are in positions 2 and 3, which is identical to positions 0 and 1. A graphical representation of KMP algorithm is shown on the next page:

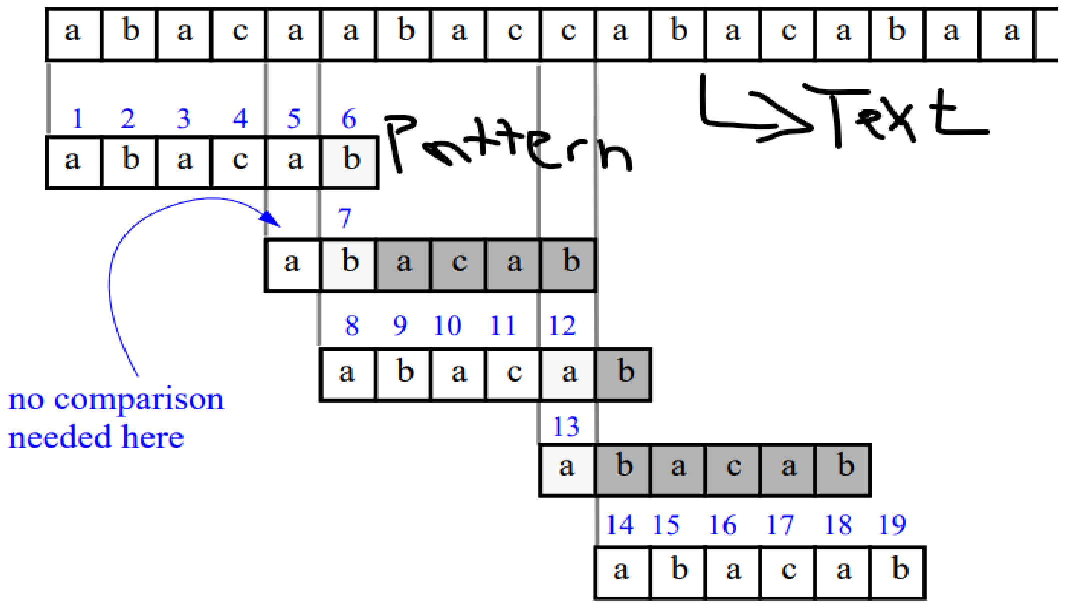

a b a c a a b a c c a b a c a b a a
1 2 3 4 5 6
Pattern
Text
7
8 9 10 11 12
13
14 15 16 17 18 19
no comparison needed here

Figure 1: Graphical representation of Knuth-Morris-Pratt Algorithm

A pseudo-code for KMP algorithm is defined below:

```
KMP(Text, Pattern, m, n)
    K = []
    n = -1
    K.append(n)
    for(k = 0; k < length(Pattern) + 1; k++)
        while(n >= 0 ^^ Pattern[n] ≠ Pattern[k - 1])
            n = K[n]
        n = n + 1
        K.append(n)
     m = 0
    for(i = 0; length(Text); i++)
        while(m >= 0 and Pattern[m] ≠ Text[i])
            m = K[m]
        m = m + 1
        if m = length(Pattern)
            m = K[m]
            return(i – m + 1, i)
```

Analysis

(i) Naïve Pattern Search Algorithm (Brute Force): To perform an analysis of the best case and worst-case time complexities for the Naïve Pattern Search algorithm we looked at a simple example below:

Best Case:

Given a table below which contains a pattern of m characters in length and a text of n characters in length. In this case, the best-case time complexity is found if there is no pattern, where there is always a mismatch on the first character, for example at m = 5:

Iterations	Text: AAAAAAAAAAAAAAAAAAAAAAAAAAAAH Pattern: OOOOH	Comparisons
1	*A*AAAAAAAAAAAAAAAAAAAAAAAAAAAH	1
	*O*OOOH	
2	A*A*AAAAAAAAAAAAAAAAAAAAAAAAAAH	1
	*O*OOOH	
3	AA*A*AAAAAAAAAAAAAAAAAAAAAAAAAH	1
	*O*OOOH	
4	AAA*A*AAAAAAAAAAAAAAAAAAAAAAAAH	1
	*O*OOOH	
5	AAAA*A*AAAAAAAAAAAAAAAAAAAAAAAH	1
	*O*OOOH	
….	….	….
N	AAAAAAAAAAAAAAAAAAAAAAAAAAAAH	1
	*O*OOOH	

Table 3: Best case time complexity for a given length of m characters and text of n characters in length.

The total number of comparisons made is n and so therefore the best time complexity is O(n). Similarly, if the pattern was found, then the best time complexity would be O(m) since the number of comparisons would be m.

Worst Case:

Provided a table below which contains a pattern of m characters in length and a text of n characters in length. In this case, the worst case is found when the algorithm compares the pattern to each substring of text of length m, for example at m = 5:

Iterations	Text: AAAAAAAAAAAAAAAAAAAAAAAAAAAAH Pattern: AAAAH	Comparisons
1	***AAAAA***AAAAAAAAAAAAAAAAAAAAAAAH	5
	AAAAH	
2	*A**AAAA***AAAAAAAAAAAAAAAAAAAAAAAH	5
	AAAAH	
3	*AA**AAAAA***AAAAAAAAAAAAAAAAAAAAAH	5
	AAAAH	
4	AAA***AAAAA***AAAAAAAAAAAAAAAAAAAAH	5

	AAAAH	
5	AAAA***AAAAA***AAAAAAAAAAAAAAAAAAH	5
	AAAAH	
….	….	….
N	AAAAAAAAAAAAAAAAAAAAAAA***AAAAH***	5
	AAAAH	

Table 4: Worst case time complexity for a given length of m characters and text of n characters in length.

So, in the worst case, the total number of comparisons made is m (n – m + 1) and so therefore the worst-case time complexity is O(mn).

(ii) Knuth-Morris-Pratt (KMP): Looking at the algorithm for KMP we notice that at every iteration through the while loop, we note the following three things happening:

1) If we let k to be n – m then, if Text[m] = Pattern[n], then n increases by 1 and m and k remains on the same position.
2) If Text[m] ≠ Pattern[n] and n > 0, then m does not change, and k increases by 1 since k is from m – n to m – f(n-1) where f is the preprocessing function.
3) If Text[m] ≠ Pattern[n] and n = 0, then n increases by 1 and k increases by 1 since m remains the same.

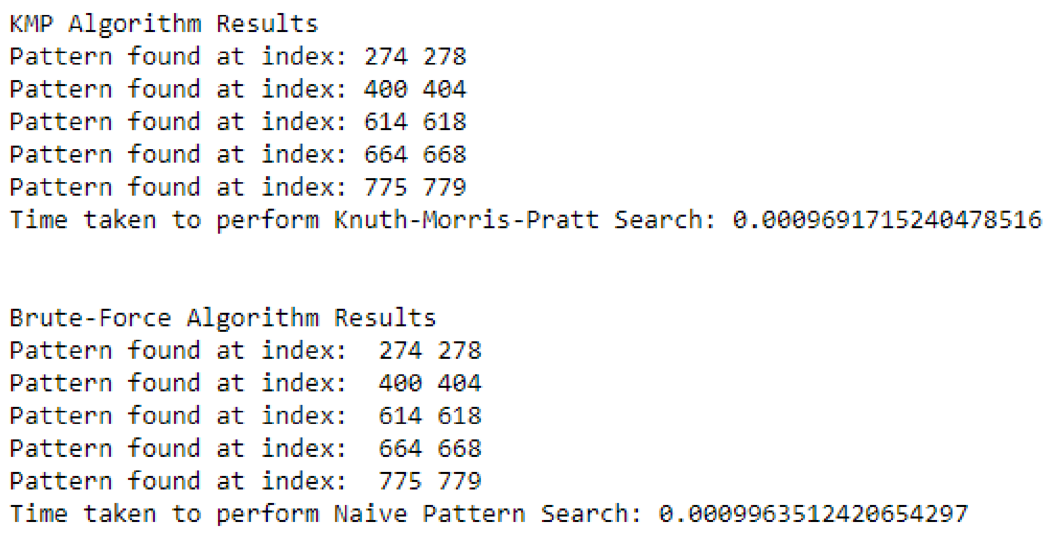
Therefore, each time through the loop either m or k increase by 1, so the greatest possible number of loops is 2n. Assuming that the preprocessing function has already been defined. In our case the pre-processing function is computed in the same way as the matching function therefore the time complexity argument is comparable. The time complexity of the preprocessing function is O(m) and the string-matching function has a time complexity of O(n) therefore the total time complexity for the KMP algorithm is O (m + n), where the worst case has a time complexity of O(n) which is a whole lot better when compared to the Naïve Pattern Search (brute-force) algorithm.

Test

In this study we were asked to test using 3 characters a, b, and c, and then randomly generate them with a string size of 1000. We were then asked to search for the string abcba. Finally, we were asked to count the number of comparisons made in the Knuth- Morris Pratt (KMP) string search, and compare it with the Naïve Pattern Search (brute-force) result of m by n. We implemented both algorithms in Python.

Results

After implementing the Naïve Pattern Search and Knuth-Morris-Pratt algorithms we obtained the following results:



```
KMP Algorithm Results
Pattern found at index: 274 278
Pattern found at index: 400 404
Pattern found at index: 614 618
Pattern found at index: 664 668
Pattern found at index: 775 779
Time taken to perform Knuth-Morris-Pratt Search: 0.0009691715240478516


Brute-Force Algorithm Results
Pattern found at index:  274 278
Pattern found at index:  400 404
Pattern found at index:  614 618
Pattern found at index:  664 668
Pattern found at index:  775 779
Time taken to perform Naive Pattern Search: 0.0009963512420654297
```

Figure 2: Results of Knuth-Morris-Pratt and Naïve Pattern Search algorithms

If we compare the results obtained using Knuth-Morris-Pratt and Naïve Pattern Search we notice that the number of comparisons made by KMP are identical to the Naïve Pattern Search, however, the time taken to perform Naïve Pattern Search is higher than the time taken to perform KMP search thus proving that the KMP algorithm is more efficient when compared to Naïve Pattern Search.

References:

https://www.cs.purdue.edu/homes/ayg/CS251/slides/chap11.pdf

https://www.codesdope.com/blog/article/kmp-algorithm/

https://www.personal.kent.edu/~rmuhamma/Algorithms/MyAlgorithms/StringMatch/kuthMP.htm

https://www.tutorialspoint.com/Knuth-Morris-Pratt-Algorithm

https://www.geeksforgeeks.org/kmp-algorithm-for-pattern-searching/

Code Implementation

Program To Implement The KMP Algorithm In Python

In [8]:

```python
import random
import string
import time
```

KMP Algorithm Implementation

In [21]:

```python
def KMP(Pattern, Chars):
    start = time.time()
   # compute the start position (number of characters)of the longest suffix that matches the prefix
   # Then store prefix and the suffix into the list K, and then set the first element of K to be -1 and the second element to be 0
    K = [] # K[n] store the value so that if the mismatch happens at n, it should move pattern Pattern K[n] characters ahead.
    n = -1
    K.append(n) #add the first element, and keep n = 0.
    for k in range (1,len(Pattern) + 1):

        # traverse all the elements in Pattern, calculate the corresponding value for each element.
        while(n >= 0 and Pattern[n] != Pattern[k - 1]): # if n = 1, if n >=1 and the current suffix does not match then try a shorter suffix
            n = K[n]
        n = n + 1 # if it matches, then the matching position should be one character ahead
        K.append(n) #record the matching position for k

    #match the string Chars with Pattern
    m = 0
    for i in range(0, len(Chars)): #traverse through the list one by one
        while(m >= 0 and Pattern[m] != Chars[i]): # if they do not match then move Pattern forward with K[m] characters and restart the comparison
            m = K[m]
        m = m + 1 #if position m matches, then move forward with the next position
        if m == len(Pattern): # if m is already the end of K (or Pattern), then a fully matched pattern is found. Continue the comparison by moving Pattern forward K[m] characters
            print("Pattern found at index:", i - m + 1, i)
            m = K[m]

    end = time.time()
    print("Time taken to perform Knuth-Morris-Pratt Search:", end - start)
```

Brute-Force Algorithm Implementation

In [80]:

```python
def bruteForce(Pattern, Chars):
    start = time.time()
     #get lengths of pattern and chars
    M = len(Pattern)
    N = len(Chars)
    # go through the Pattern[]
    for i in range(N - M + 1):
        j = 0
        # For current index i, check for pattern match
        while(j < M):
            if (Chars[i + j] != Pattern[j]):
                break
            j = j + 1
        if (j == M):
            print("Pattern found at index: ", i, i + j - 1)

    end = time.time()
    print("Time taken to perform Naive Pattern Search:", end - start)
```

Random 1000 Letter Generation

In [87]:

```
letters = "abc"
Chars = ''.join(random.choice(letters) for i in range(1000))
print(Chars)
Pattern = "abcba"
```

```
acacbbbcccbcacaaabcccacaccaaacaccabaaccaaabbbbaabbbcabbaaccaacbabcbcccccbbcabcacbbbbcbcccbccccabbabbaccacbbbacacbcbcbabcacbbbacbaabbaacccbcbbccccbbcabaccbcbcbccccaabbcbabbcbbaaaccabaabbb
ccaccaabaababaccccccabaccbccabaccacaacaacaabcbaccacbcacbcbabbaacabcccabcccccbbcccbccaacccbabbcbcbacccbbcbabcaccabbcaccaacabbbccbccabbbcbcabbcbcbaaacbbcabcaabcbbabaacbbbabccaabcaaacccbac
aaabaabaabaaccccbabccbcbbbabccccaacbbabacbbaaccababcbbbbabbbaabaaabbaabccccbcaabcccbbaabbcbaabccbaacacbbbbaabacccccccbcbabcacaababcbcaacbbbabacccacbcbbcabcbccbabacabcaababbababacaaaccba
aaaaabacaaaaabcabacbbbcbbbaccbcaccbcabbbbccbcabbcacabcaaccbbababbbcbccaacbbbbbaabcaaacaaacbbaaaccbcaaabaaaaccbbabccbcabbccabaaccabcacabaaaccaccabccacacbbbccabbbabbaacbacabccacaabbbbbabb
cabbacccbbaabacabcbbaacaacaaabcbbbabaccacbbabbbacccaacaacabaaaccbbcbccbccabcbacbaaccaababcbabaccaabacbaaabcbaacbbcaabbaacbabaaccaaacbabaabbccbabacbccbccbacacbabcaaabbababbbbcacaccbabbbbc
caccacccabbbbabcbabaacabbabaccacaabbcabbbbabbabbcbaabbcccbacabbccbbaba
```

Test

In [88]:

```
def main():
        print("KMP Algorithm Results")
        KMP(Pattern, Chars)
        print("\n")
        print("Brute-Force Algorithm Results")
        bruteForce(Pattern, Chars)
```

In [89]:

```
if __name__ == '__main__':
    main()
```

```
KMP Algorithm Results
Pattern found at index: 228 232
Pattern found at index: 817 821
Pattern found at index: 831 835
Pattern found at index: 848 852
Pattern found at index: 943 947
Time taken to perform Knuth-Morris-Pratt Search: 0.0010294914245605469


Brute-Force Algorithm Results
Pattern found at index:  228 232
Pattern found at index:  817 821
Pattern found at index:  831 835
Pattern found at index:  848 852
Pattern found at index:  943 947
Time taken to perform Naive Pattern Search: 0.0019614696502685547
```