



CSE408

String Matching

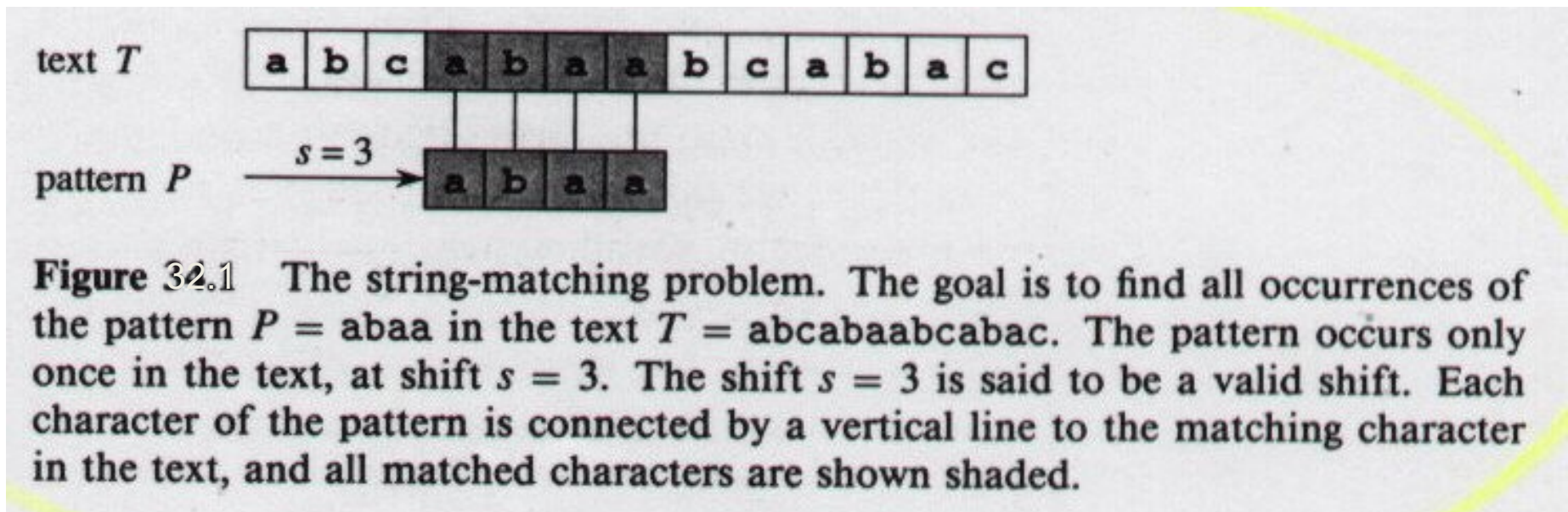
Algorithm

Lecture # 5&6

String Matching Problem



Motivations: text-editing, pattern matching in DNA sequences



Text: array $T[1\dots n]$

$$n > m$$

Pattern: array $P[1\dots m]$

Array Element: Character from finite alphabet Σ

Pattern P occurs with shift s in T if $P[1\dots m] = T[s+1\dots s+m]$ $n > m$

String Matching Algorithms



- Naive Algorithm
 - Worst-case running time in $O((n-m+1) m)$
- Rabin-Karp
 - Worst-case running time in $O((n-m+1) m)$
 - Better than this on average and in practice
- Knuth-Morris-Pratt
 - best-case running time in $O(n + m)$

Notation & Terminology



- Σ^* = set of all finite-length strings formed using characters from alphabet Σ
- Empty string: ε
- $|x|$ = length of string x
- w is a prefix of x : $w \ x$
- w is a suffix of x : $w \ x$
- prefix, suffix are *transitive*

ab abcca

cca abcca

Naive String Matching



NAIVE-STRING-MATCHER(T, P)

```
1  $n \leftarrow \text{length}[T]$ 
2  $m \leftarrow \text{length}[P]$ 
3 for  $s \leftarrow 0$  to  $n - m$ 
4     do if  $P[1..m] = T[s + 1..s + m]$ 
5         then print "Pattern occurs with shift"  $s$ 
```

worst-case running time is in $\Theta((n-m+1)m)$

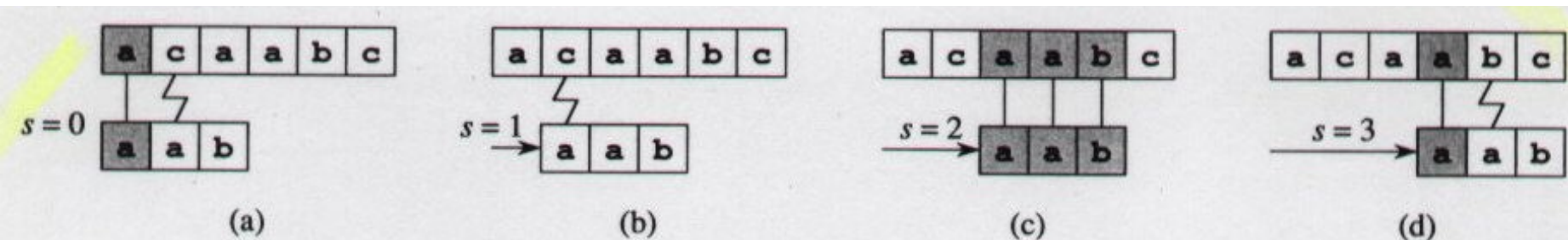


Figure 32.3 The operation of the naive string matcher for the pattern $P = aab$ and the text $T = acaabc$. We can imagine the pattern P as a “template” that we slide next to the text. Parts (a)–(d) show the four successive alignments tried by the naive string matcher. In each part, vertical lines connect corresponding regions found to match (shown shaded), and a jagged line connects the first mismatched character found, if any. One occurrence of the pattern is found, at shift $s = 2$, shown in part (c).

Rabin-Karp Algorithm



- Assume each character is digit in radix-d notation (e.g. $d=10$)
- p = decimal value of pattern
- t_s = decimal value of substring $T[s+1..s+m]$ for $s = 0, 1, \dots, n-m$
- Strategy:
 - compute p in $O(m)$ time (which is in $O(n)$)
 - compute all t_i values in total of $O(n)$ time
 - find all valid shifts s in $O(n)$ time by comparing p with each t_s
- Compute p in $O(m)$ time using Horner's rule:
 - $p = P[m] + d(P[m-1] + d(P[m-2] + \dots + d(P[2] + dP[1])))$
- Compute t_0 similarly from $T[1..m]$ in $O(m)$ time
- Compute remaining t_i 's in $O(n-m)$ time
 - $t_{s+1} = d(t_s - d^{m-1}T[s+1]) + T[s+m+1]$

Rabin-Karp Algorithm



But... p, t_s may be large, so use mod

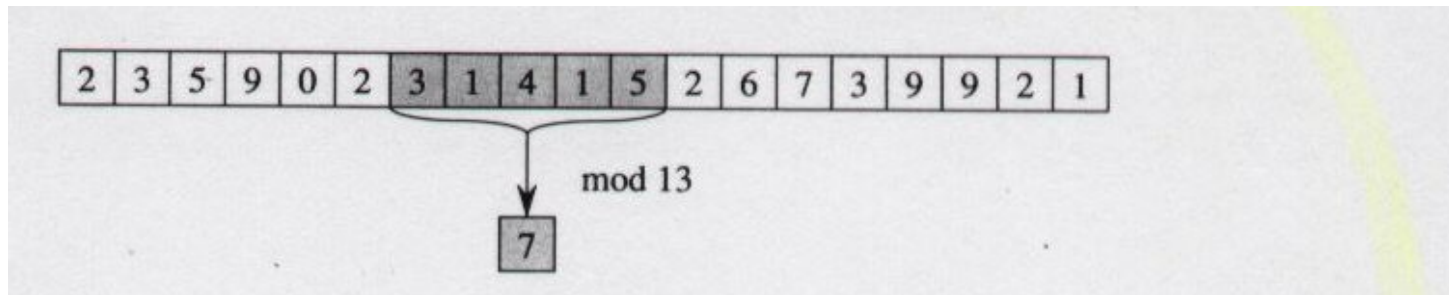


Figure 3.4.4 The Rabin-Karp algorithm. Each character is a decimal digit, and we compute values modulo 13. (a) A text string. A window of length 5 is shown shaded. The numerical value of the shaded number is computed modulo 13, yielding the value 7. (b) The same text string with values computed modulo 13 for

Rabin-Karp Algorithm (continued)



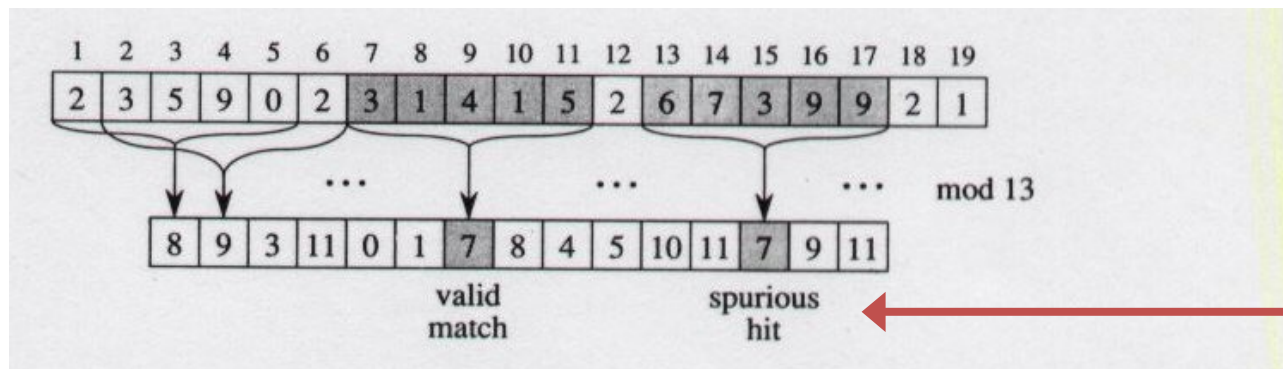
But...

$$t_{s+1} = d(t_s - d^{m-1}T[s+1]) + T[s+m+1]$$



$$t_{s+1} = (d(t_s - T[s+1]h) + T[s+m+1]) \bmod q ,$$

(34.2)

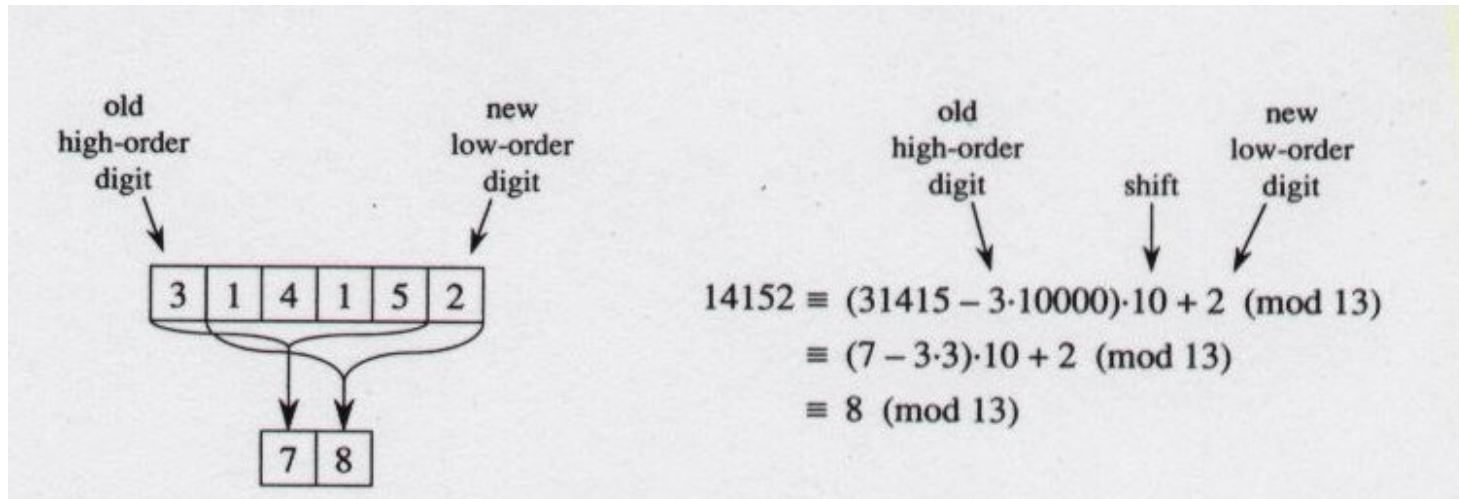


$p = 31415$

spurious
hit

ing the value 7. (b) The same text string with values computed modulo 13 for each possible position of a length-5 window. Assuming the pattern $P = 31415$, we look for windows whose value modulo 13 is 7, since $31415 \equiv 7 \pmod{13}$. Two such windows are found, shown shaded in the figure. The first, beginning at text position 7, is indeed an occurrence of the pattern, while the second, beginning at text position 13, is a spurious hit. (c) Computing the value for a window in con-

Rabin-Karp Algorithm (continued)



text position 13, is a spurious hit. (c) Computing the value for a window in constant time, given the value for the previous window. The first window has value 31415. Dropping the high-order digit 3, shifting left (multiplying by 10), and then adding in the low-order digit 2 gives us the new value 14152. All computations are performed modulo 13, however, so the value for the first window is 7, and the value computed for the new window is 8.

Rabin-Karp Algorithm (continued)



RABIN-KARP-MATCHER(T, P, d, q) d is radix q is modulus

```
1   $n \leftarrow \text{length}[T]$ 
2   $m \leftarrow \text{length}[P]$ 
3   $h \leftarrow d^{m-1} \bmod q$     high-order digit position for m-digit window
4   $p \leftarrow 0$ 
5   $t_0 \leftarrow 0$ 
6  for  $i \leftarrow 1$  to  $m$     Preprocessing
7      do  $p \leftarrow (dp + P[i]) \bmod q$ 
8           $t_0 \leftarrow (dt_0 + T[i]) \bmod q$ 
9  for  $s \leftarrow 0$  to  $n - m$     Matching loop invariant: when line 10 executed
10     do if  $p = t_s$      $t_s = T[s+1..s+m] \bmod q$ 
11         then if  $P[1..m] = T[s+1..s+m]$     rule out spurious hit
12             then "Pattern occurs with shift"  $s$ 
13         if  $s < n - m$ 
14             then  $t_{s+1} \leftarrow (d(t_s - T[s+1])h + T[s+m+1]) \bmod q$ 
```

$\Theta(m)$ in $\Theta(n)$ →

$\Theta(m)$

$\Theta((n-m+1)m)$

$\Theta(m)$

Try all
possible
shifts

What input generates worst case?

worst-case running time is in $\Theta((n-m+1)m)$

Rabin-Karp Algorithm (continued)



Worst Case

$\Theta(m)$ in $\Theta(n)$ →

$\Theta(m)$

$\Theta((n-m+1)m)$ $\Theta(m)$

Try all possible shifts

```

RABIN-KARP-MATCHER( $T, P, d, q$ )     $d$  is radix   $q$  is modulus
1   $n \leftarrow \text{length}[T]$ 
2   $m \leftarrow \text{length}[P]$ 
3   $h \leftarrow d^{m-1} \bmod q$     high-order digit position for m-digit window
4   $p \leftarrow 0$ 
5   $t_0 \leftarrow 0$ 
6  for  $i \leftarrow 1$  to  $m$     Preprocessing
7      do  $p \leftarrow (dp + P[i]) \bmod q$ 
8       $t_0 \leftarrow (dt_0 + T[i]) \bmod q$ 
9  for  $s \leftarrow 0$  to  $n - m$     Matching loop invariant: when line 10 executed
10     do if  $p = t_s$      $t_s = T[s+1..s+m] \bmod q$ 
11         then if  $P[1..m] = T[s+1..s+m]$     rule out spurious hit
12             then "Pattern occurs with shift"  $s$ 
13         if  $s < n - m$ 
14             then  $t_{s+1} \leftarrow (d(t_s - T[s+1])h + T[s+m+1]) \bmod q$ 
    
```

Average Case

Assume reducing mod q is like random mapping from Σ^* to Z_q

Estimate (chance that $t_s = p \bmod q$) = $1/q$ → # spurious hits is in $O(n/q)$

Expected matching time = $O(n) + O(m(v + n/q))$ ($v = \#$ valid shifts)

If v is in $O(1)$ and $q \geq m$ → average-case running time is in $O(n+m)$

The Knuth-Morris-Pratt Algorithm



Knuth, Morris and Pratt proposed a linear time algorithm for the string matching problem.

A matching time of $O(n)$ is achieved by avoiding comparisons with elements of 'S' that have previously been involved in comparison with some element of the pattern 'p' to be matched. i.e., backtracking on the string 'S' never occurs

Components of KMP algorithm



- The prefix function, Π

The prefix function, Π for a pattern encapsulates knowledge about how the pattern matches against shifts of itself. This information can be used to avoid useless shifts of the pattern 'p'. In other words, this enables avoiding backtracking on the string 'S'.

- The KMP Matcher

With string 'S', pattern 'p' and prefix function ' Π ' as inputs, finds the occurrence of 'p' in 'S' and returns the number of shifts of 'p' after which occurrence is found.

The prefix function, Π



Following pseudocode computes the prefix function, Π :

Compute-Prefix-Function (p)

```
1  $m \leftarrow \text{length}[p]$            //'p' pattern to be matched
2  $\Pi[1] \leftarrow 0$ 
3  $k \leftarrow 0$ 
4   for  $q \leftarrow 2$  to  $m$ 
5       do while  $k > 0$  and  $p[k+1] \neq p[q]$ 
6           do  $k \leftarrow \Pi[k]$ 
7           if  $p[k+1] = p[q]$ 
8               then  $k \leftarrow k + 1$ 
9            $\Pi[q] \leftarrow k$ 
10  return  $\Pi$ 
```

Example: compute Π for the pattern 'p' below:

p

a	b	a	b	a	c	a
---	---	---	---	---	---	---

Initially: $m = \text{length}[p] = 7$

$\Pi[1] = 0$

$k = 0$

Step 1: $q = 2, k=0$

q	1	2	3	4	5	6	7
p	a	b	a	b	a	c	a
Π	0	0					

$\Pi[2] = 0$

q	1	2	3	4	5	6	7
p	a	b	a	b	a	c	a
Π	0	0	1				

Step 2: $q = 3, k = 0,$

$\Pi[3] = 1$

q	1	2	3	4	5	6	7
p	a	b	a	b	a	c	A
Π	0	0	1	2			

Step 4: $q = 5, k = 2$
 $\Pi[5] = 3$

q	1	2	3	4	5	6	7
p	a	b	a	b	a	c	a
Π	0	0	1	2	3		

Step 5: $q = 6, k = 3$
 $\Pi[6] = 1$

q	1	2	3	4	5	6	7
p	a	b	a	b	a	c	a
Π	0	0	1	2	3	1	

Step 6: $q = 7, k = 1$
 $\Pi[7] = 1$

q	1	2	3	4	5	6	7
p	a	b	a	b	a	c	a
Π	0	0	1	2	3	1	1

After iterating 6 times, the prefix function computation is complete: \rightarrow

q	1	2	3	4	5	6	7
p	a	b	A	b	a	c	a
Π	0	0	1	2	3	1	1

The KMP Matcher



The KMP Matcher, with pattern 'p', string 'S' and prefix function ' Π ' as input, finds a match of p in S. Following pseudocode computes the matching component of KMP algorithm:

KMP-Matcher(S,p)

```
1  $n \leftarrow \text{length}[S]$ 
2  $m \leftarrow \text{length}[p]$ 
3  $\Pi \leftarrow \text{Compute-Prefix-Function}(p)$ 
4  $q \leftarrow 0$  //number of characters matched
5 for  $i \leftarrow 1$  to  $n$  //scan S from left to right
6   do while  $q > 0$  and  $p[q+1] \neq S[i]$ 
7     do  $q \leftarrow \Pi[q]$  //next character does not match
8   if  $p[q+1] = S[i]$ 
9     then  $q \leftarrow q + 1$  //next character matches
10  if  $q = m$  //is all of p matched?
11    then print "Pattern occurs with shift"  $i - m$ 
12     $q \leftarrow \Pi[q]$  // look for the next match
```

Note: KMP finds every occurrence of a 'p' in 'S'. That is why KMP does not terminate in step 12, rather it searches remainder of 'S' for any more occurrences of 'p'.

Illustration: given a String 'S' and pattern 'p' as follows:

S

b	a	c	b	a	b	a	b	a	b	a	c	a	c	a
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

p

a	b	a	b	a	c	a
---	---	---	---	---	---	---

Let us execute the KMP algorithm to find whether 'p' occurs in 'S'.

For 'p' the prefix function, Π was computed previously and is as follows:

q	1	2	3	4	5	6	7
p	a	b	A	b	a	c	a
Π	0	0	1	2	3	1	1

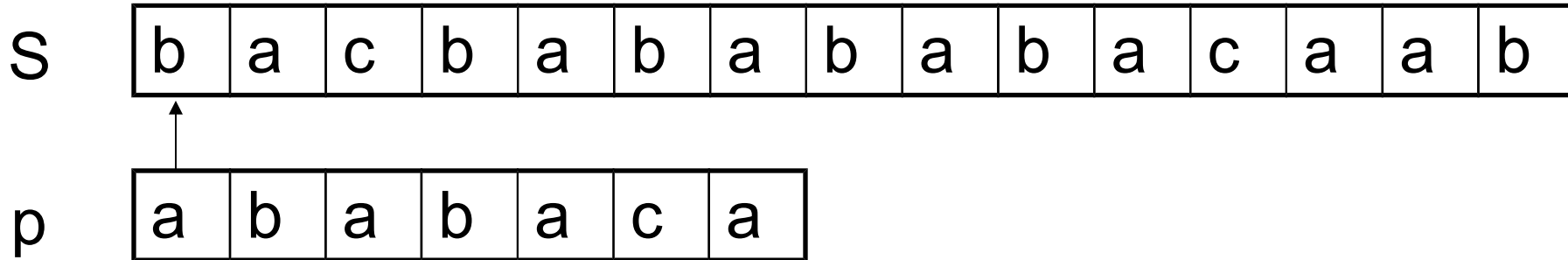
Initially: $n = \text{size of } S = 15;$

$m = \text{size of } p = 7$



Step 1: $i = 1, q = 0$

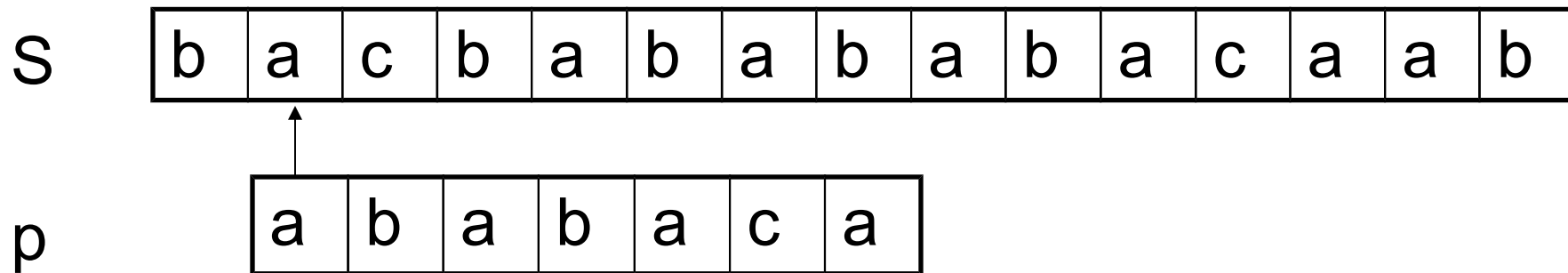
comparing $p[1]$ with $S[1]$



$P[1]$ does not match with $S[1]$. 'p' will be shifted one position to the right.

Step 2: $i = 2, q = 0$

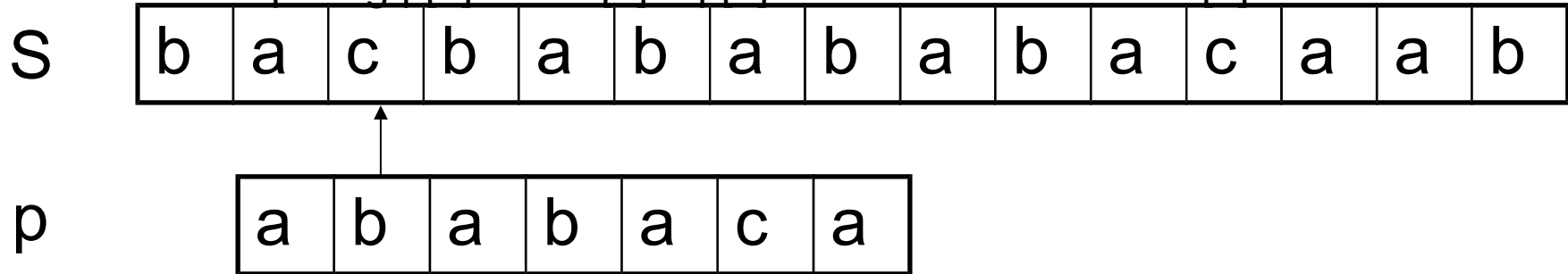
comparing $p[1]$ with $S[2]$



$P[1]$ matches $S[2]$. Since there is a match, p is not shifted.

Step 3: $i = 3, q = 1$

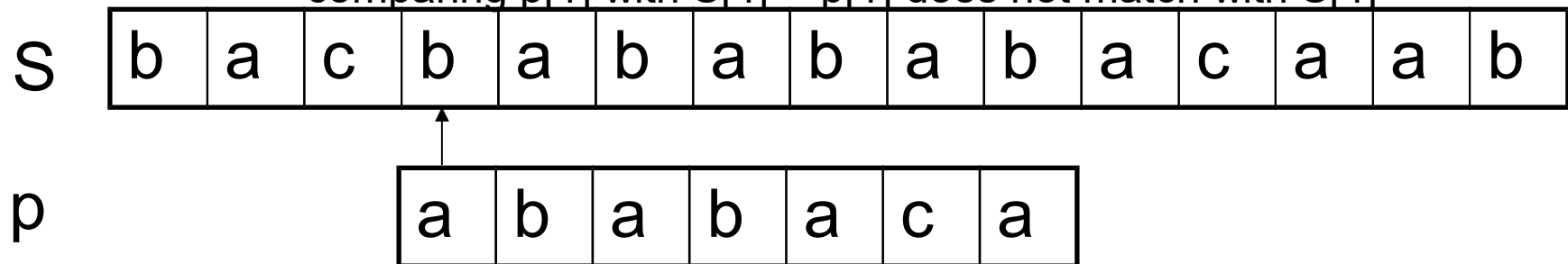
Comparing $p[2]$ with $S[3]$ $p[2]$ does not match with $S[3]$



Backtracking on p, comparing $p[1]$ and $S[3]$

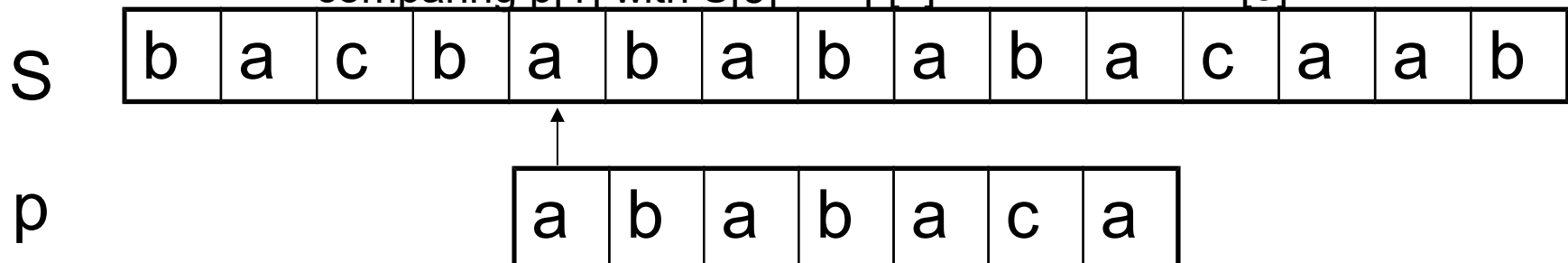
Step 4: $i = 4, q = 0$

comparing $p[1]$ with $S[4]$ $p[1]$ does not match with $S[4]$



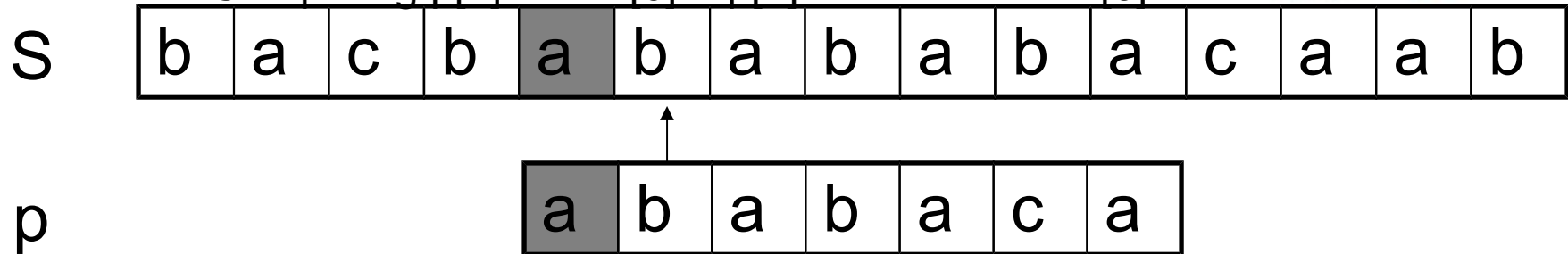
Step 5: $i = 5, q = 0$

comparing $p[1]$ with $S[5]$ $p[1]$ matches with $S[5]$



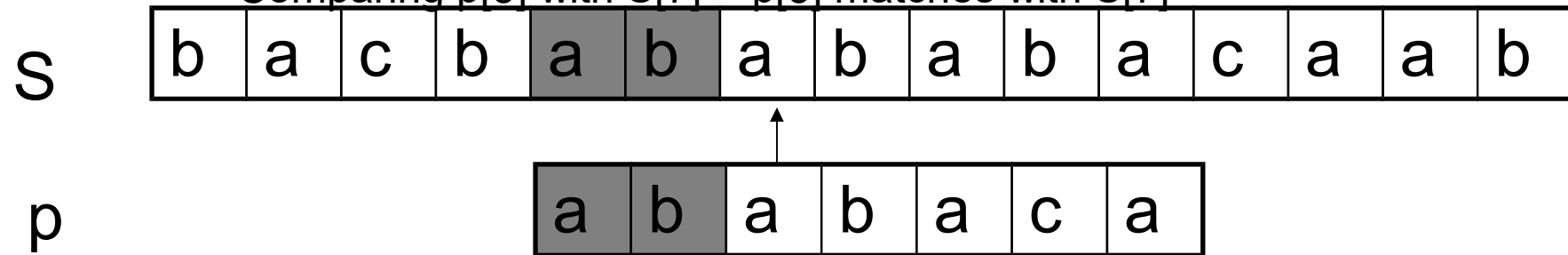
Step 6: $i = 6, q = 1$

Comparing $p[2]$ with $S[6]$ $p[2]$ matches with $S[6]$



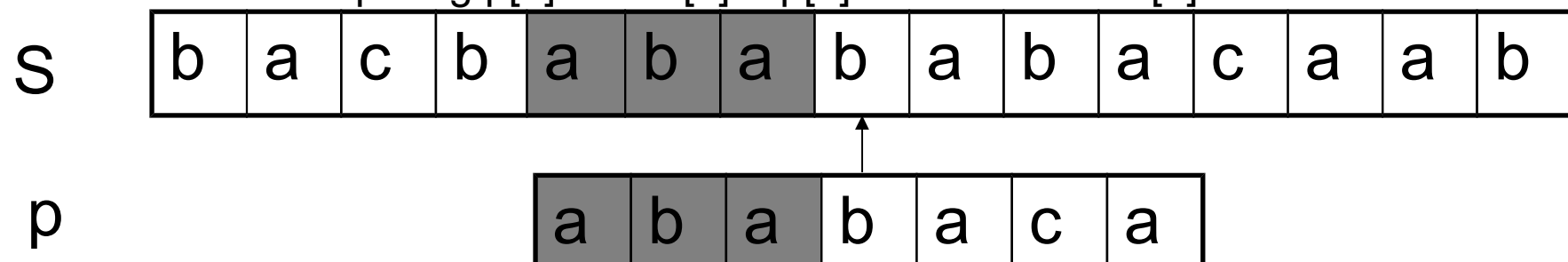
Step 7: $i = 7, q = 2$

Comparing $p[3]$ with $S[7]$ $p[3]$ matches with $S[7]$

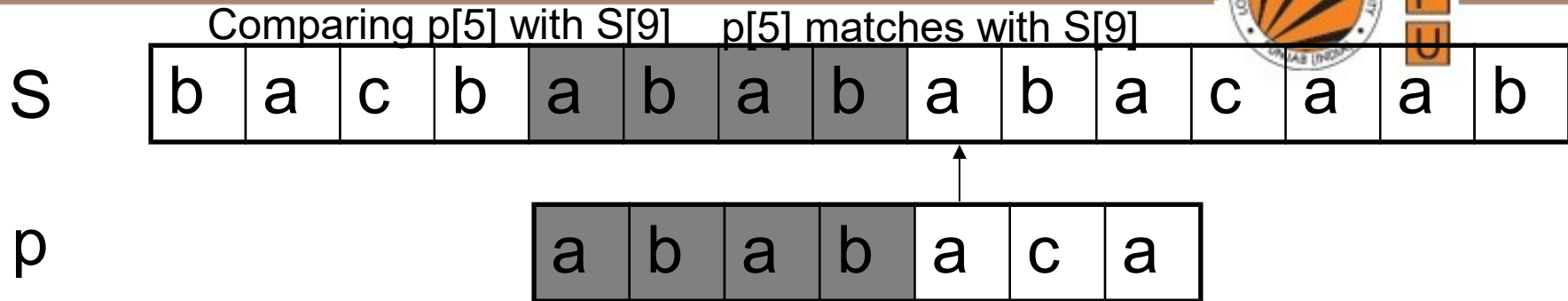


Step 8: $i = 8, q = 3$

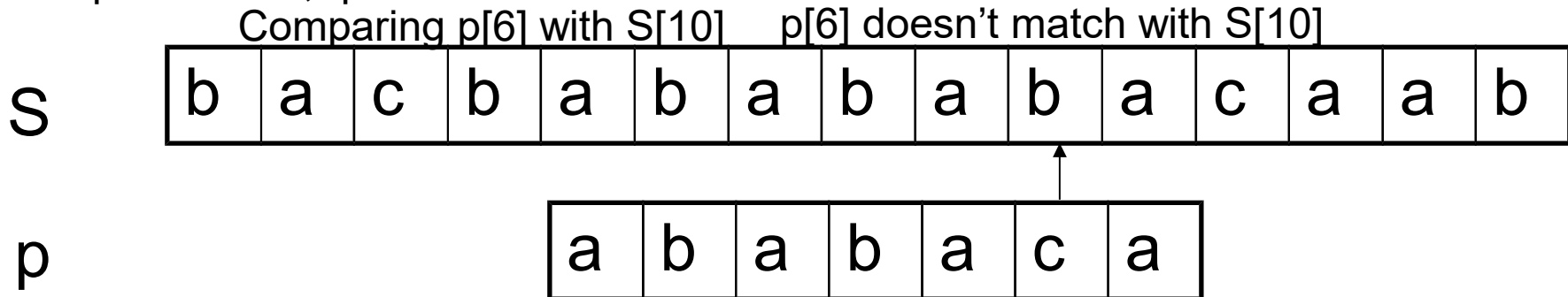
Comparing $p[4]$ with $S[8]$ $p[4]$ matches with $S[8]$



Step 9: $i = 9, q = 4$

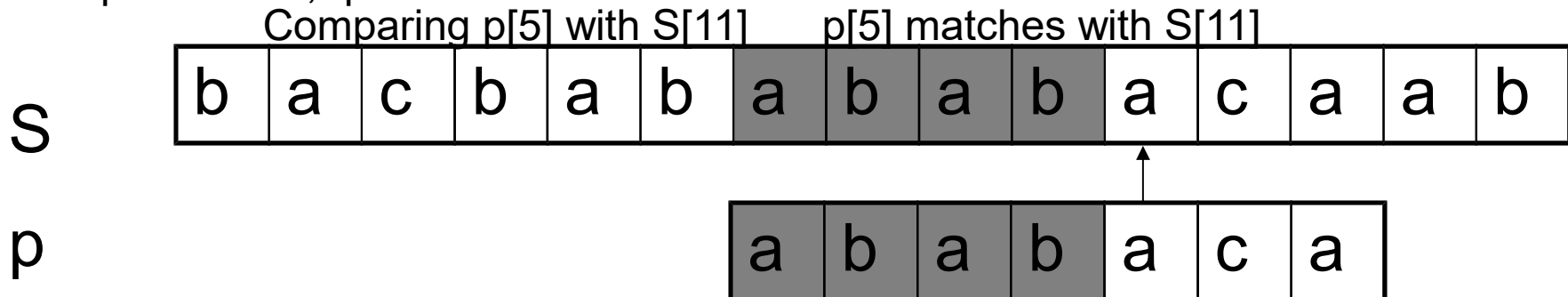


Step 10: $i = 10, q = 5$

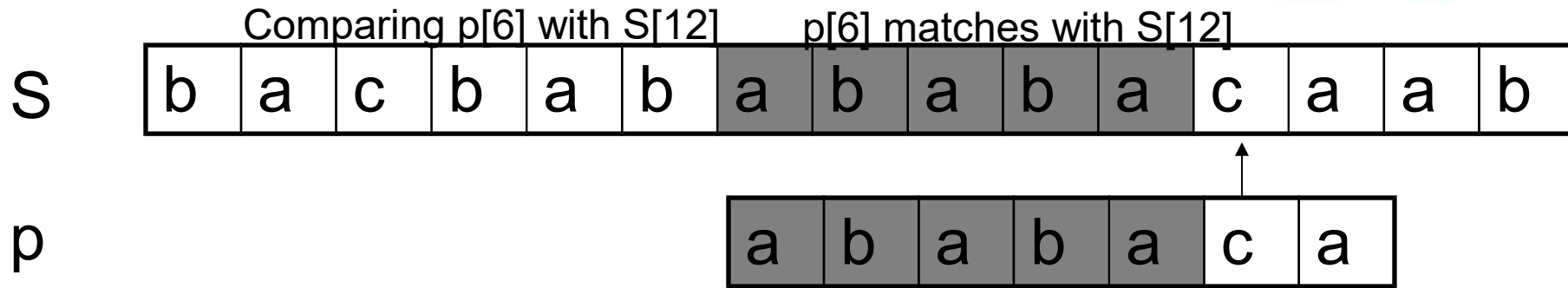


Backtracking on p , comparing $p[4]$ with $S[10]$ because after mismatch $q = \Pi[5] = 3$

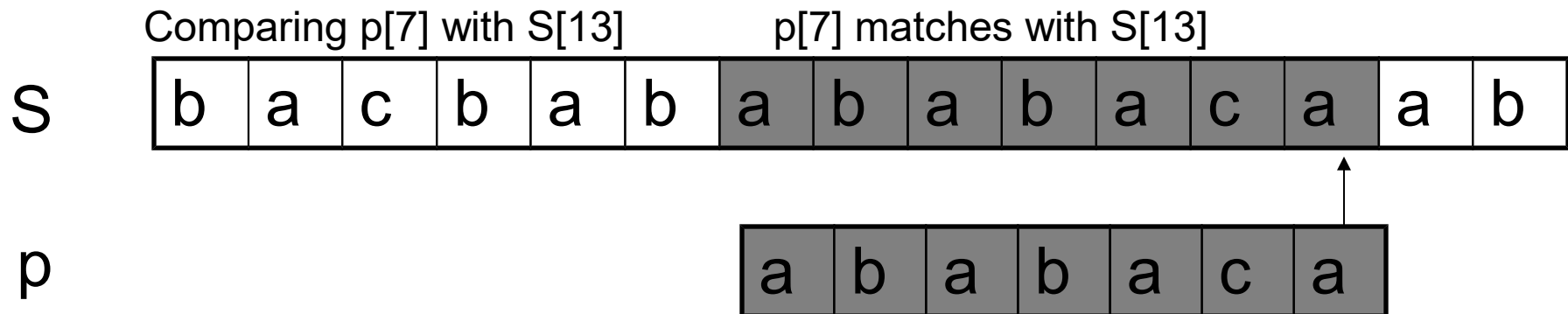
Step 11: $i = 11, q = 4$



Step 12: $i = 12, q = 5$



Step 13: $i = 13, q = 6$



Pattern 'p' has been found to completely occur in string 'S'. The total number of shifts that took place for the match to be found are: $i - m = 13 - 7 = 6$ shifts.

Running - time analysis



- Compute-Prefix-Function (Π)

```
1 m  $\leftarrow$  length[p]      //p' pattern to be matched
2  $\Pi[1] \leftarrow 0$ 
3 k  $\leftarrow 0$ 
4   for q  $\leftarrow 2$  to m
5     do while k > 0 and p[k+1] != p[q]
6       do k  $\leftarrow \Pi[k]$ 
7       if p[k+1] = p[q]
8         then k  $\leftarrow$  k + 1
9        $\Pi[q] \leftarrow$  k
10  return  $\Pi$ 
```

- KMP Matcher

```
1 n  $\leftarrow$  length[S]
2 m  $\leftarrow$  length[p]
3  $\Pi \leftarrow$  Compute-Prefix-Function(p)
4 q  $\leftarrow 0$ 
5 for i  $\leftarrow 1$  to n
6   do while q > 0 and p[q+1] != S[i]
7     do q  $\leftarrow \Pi[q]$ 
8   if p[q+1] = S[i]
9     then q  $\leftarrow$  q + 1
10  if q = m
11    then print "Pattern occurs with shift" i - m
12    q  $\leftarrow \Pi[q]$ 
```

In the above pseudocode for computing the prefix function, the for loop beginning in step 4 runs m times, as Step 1 to step 3 take constant time. Hence the running time as the length of prefix string (S) is $\Theta(m)$.
The for loop beginning in step 5 runs n times, as Step 1 to step 4 take constant time, the running time is dominated by this for loop. Thus running time of matching function is $\Theta(n)$.

Knuth-Morris-Pratt Algorithm



KMP-MATCHER(T, P)

```
1   $n \leftarrow \text{length}[T]$ 
2   $m \leftarrow \text{length}[P]$ 
3   $\pi \leftarrow \text{COMPUTE-PREFIX-FUNCTION}(P)$ 
4   $q \leftarrow 0$     # characters matched
5  for  $i \leftarrow 1$  to  $n$     scan text left-to-right
6      do while  $q > 0$  and  $P[q + 1] \neq T[i]$ 
7          do  $q \leftarrow \pi[q]$     next character does not match
8      if  $P[q + 1] = T[i]$ 
9          then  $q \leftarrow q + 1$     next character matches
10     if  $q = m$     Is all of  $P$  matched?
11         then print "Pattern occurs with shift"  $i - m$ 
12          $q \leftarrow \pi[q]$     Look for next match
```

$\Theta(m)$ in $\Theta(n)$ →

using
amortized
analysis

$\Theta(m+n)$

$\Theta(n)$

using
amortized
analysis

Knuth-Morris-Pratt Algorithm



Worst Case *Amortized Analysis* *Potential Method*

$$\Phi(k) = k \quad k = \text{current state of algorithm}$$

COMPUTE-PREFIX-FUNCTION(P)

```
1   $m \leftarrow \text{length}[P]$ 
2   $\pi[1] \leftarrow 0$ 
3   $k \leftarrow 0$     initial potential value
4  for  $q \leftarrow 2$  to  $m$ 
5      do while  $k > 0$  and  $P[k + 1] \neq P[q]$ 
6          do  $k \leftarrow \pi[k]$     potential decreases
7          if  $P[k + 1] = P[q]$     potential
8              then  $k \leftarrow k + 1$     increases by
9                   $\pi[q] \leftarrow k$      $\leq 1$  in each
10 return  $\pi$     execution of
                   for loop body
```

*Potential is never negative
since $\pi(k) \geq 0$ for all k*

*amortized
cost of loop
body is in
 $O(1)$*

*$\Theta(m)$ loop
iterations*

$\Theta(m)$
in
 $\Theta(n)$



Thank You !!!