

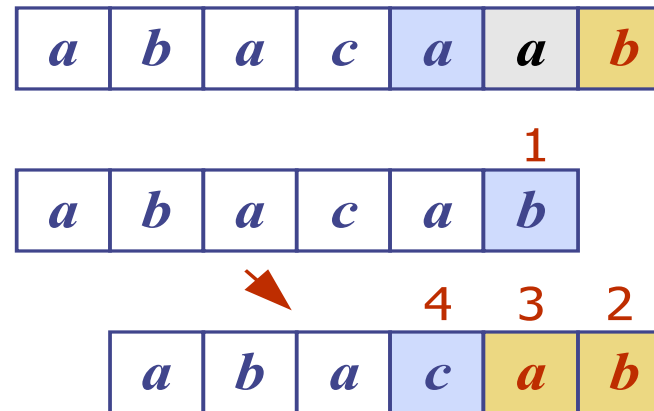
COMP9024: Data Structures and Algorithms

Text Processing

Contents

- Pattern matching
- Tries
- Greedy method
- Text compression
- Dynamic programming

Pattern Matching



Strings

- A string is a sequence of characters
- Examples of strings:
 - Java program
 - HTML document
 - DNA sequence
 - Digitized image
- An alphabet Σ is the set of possible characters for a family of strings
- Example of alphabets:
 - ASCII
 - Unicode
 - $\{0, 1\}$
 - $\{A, C, G, T\}$
- Let P be a string of size m
 - A substring $P[i..j]$ of P is the subsequence of P consisting of the characters with ranks between i and j
 - A prefix of P is a substring of the type $P[0..i]$
 - A suffix of P is a substring of the type $P[i..m-1]$
- Given strings T (text) and P (pattern), the pattern matching problem consists of finding a substring of T equal to P
- Applications:
 - Text editors
 - Search engines
 - Biological research

Brute-Force Pattern Matching

- The brute-force pattern matching algorithm compares the pattern P with the text T for each possible shift of P relative to T , until either
 - a match is found, or
 - all placements of the pattern have been tried
- Brute-force pattern matching runs in time $O(nm)$
- Example of worst case:
 - $T = aaa \dots ah$
 - $P = aaah$
 - may occur in images and DNA sequences
 - unlikely in English text

Algorithm *BruteForceMatch*(T, P)

Input text T of size n and pattern P of size m

Output starting index of a substring of T equal to P or -1 if no such substring exists

```
{ for (  $i = 0$ ;  $i < n - m + 1$ ;  $i++$  )  
  { // test shift  $i$  of the pattern  
     $j = 0$ ;  
    while (  $j < m \wedge T[i + j] = P[j]$  )  
       $j = j + 1$ ;  
    if (  $j = m$  )  
      return  $i$ ; // match at  $i$   
  }  
  return  $-1$  // no match anywhere  
}
```

Boyer-Moore Heuristics

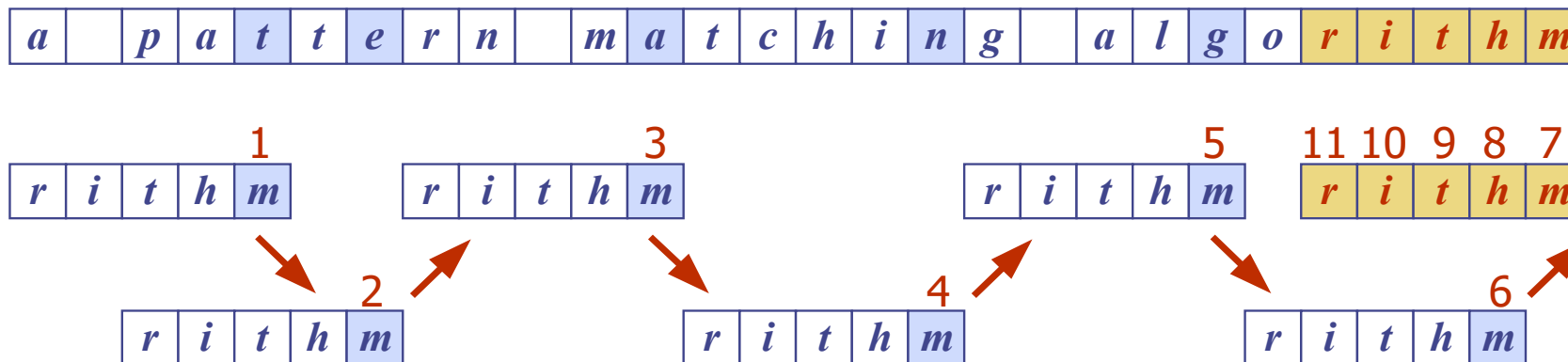
- The Boyer-Moore's pattern matching algorithm is based on two heuristics

Looking-glass heuristic: Compare P with a subsequence of T moving backwards

Character-jump heuristic: When a mismatch occurs at $T[i] = c$

- If P contains c , shift P to align the last occurrence of c in P with $T[i]$
- Else, shift P to align $P[0]$ with $T[i + 1]$

- Example



Last-Occurrence Function

- Boyer-Moore's algorithm preprocesses the pattern P and the alphabet Σ to build the last-occurrence function L mapping Σ to integers, where $L(c)$ is defined as
 - the largest index i such that $P[i] = c$ or
 - -1 if no such index exists

- Example:

- $\Sigma = \{a, b, c, d\}$
- $P = abacab$

c	a	b	c	d
$L(c)$	4	5	3	-1

- The last-occurrence function can be represented by an array indexed by the numeric codes of the characters
- The last-occurrence function can be computed in time $O(m + s)$, where m is the size of P and s is the size of Σ

The Boyer-Moore Algorithm

Algorithm *BoyerMooreMatch*(T, P, Σ)

{ $L = \text{lastOccurrenceFunction}(P, \Sigma)$

$i = m - 1$

$j = m - 1$

repeat

if ($T[i] = P[j]$)

{ if ($j = 0$)

return i // match at i

else

{ $i = i - 1$;

$j = j - 1$; }

}

else // character-jump

{ $l = L[T[i]]$;

$i = i + m - \min(j, 1 + l)$;

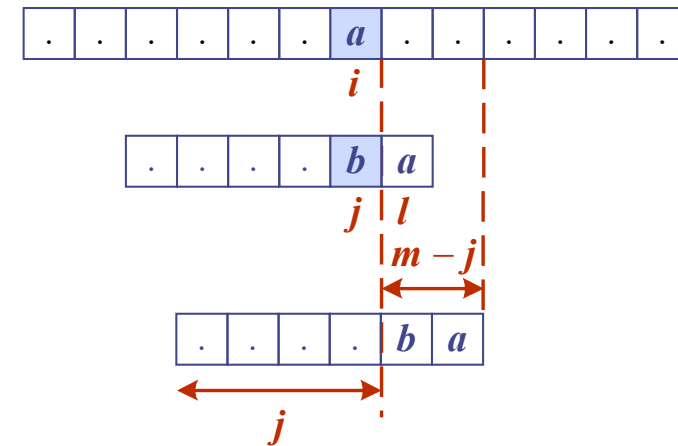
$j = m - 1$; }

until ($i > n - 1$)

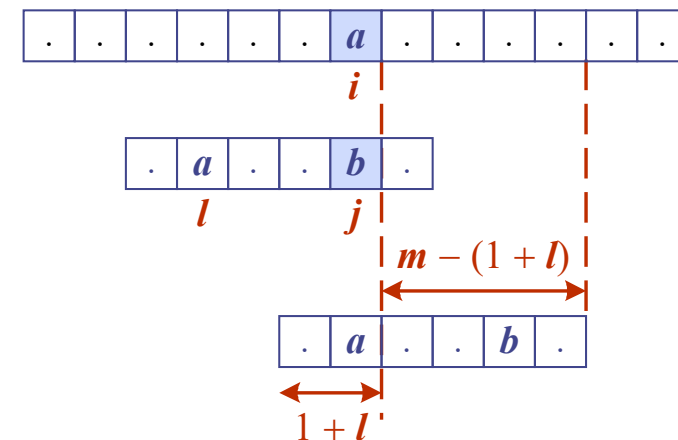
return -1 // no match

}

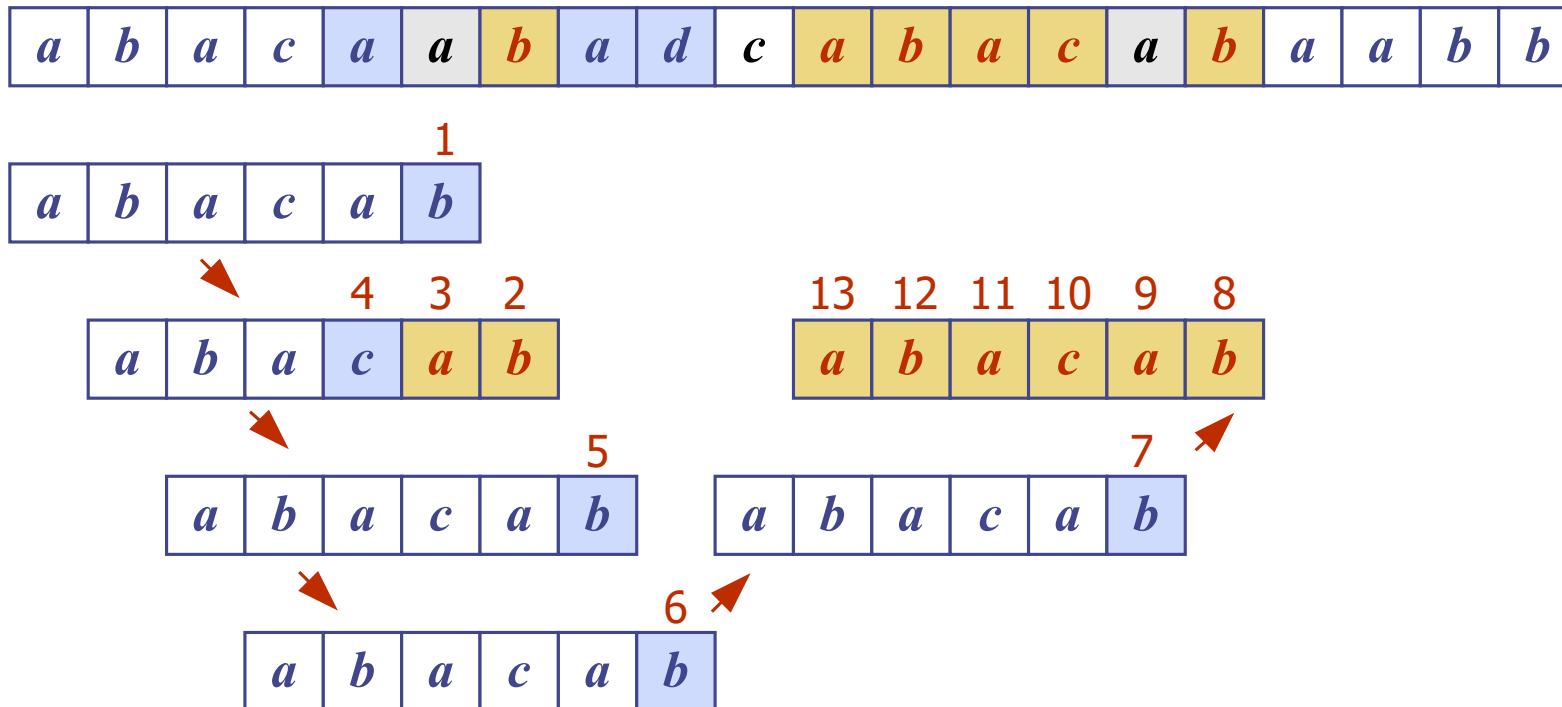
Case 1: $j \leq 1 + l$



Case 2: $1 + l \leq j$

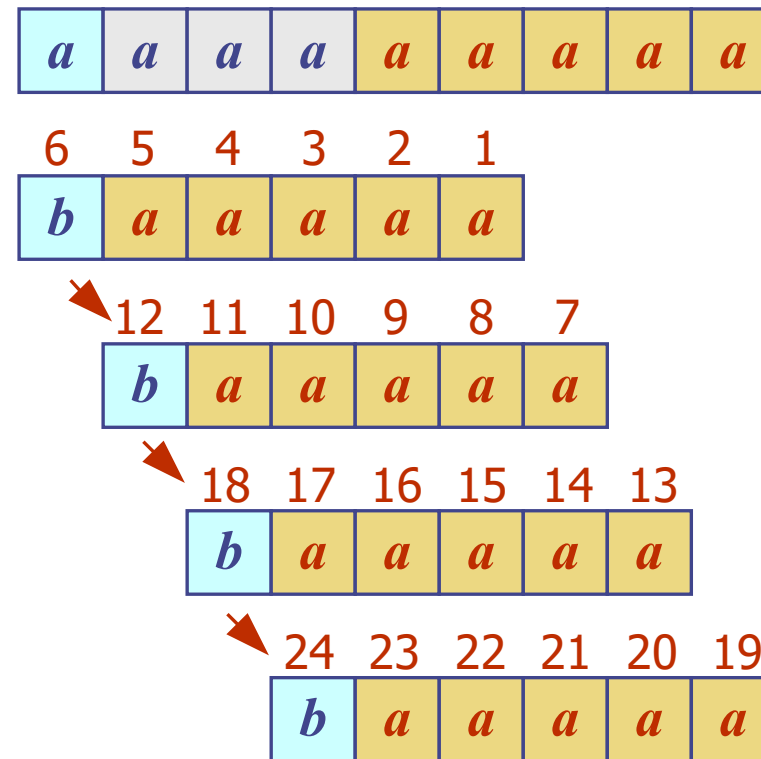


Example



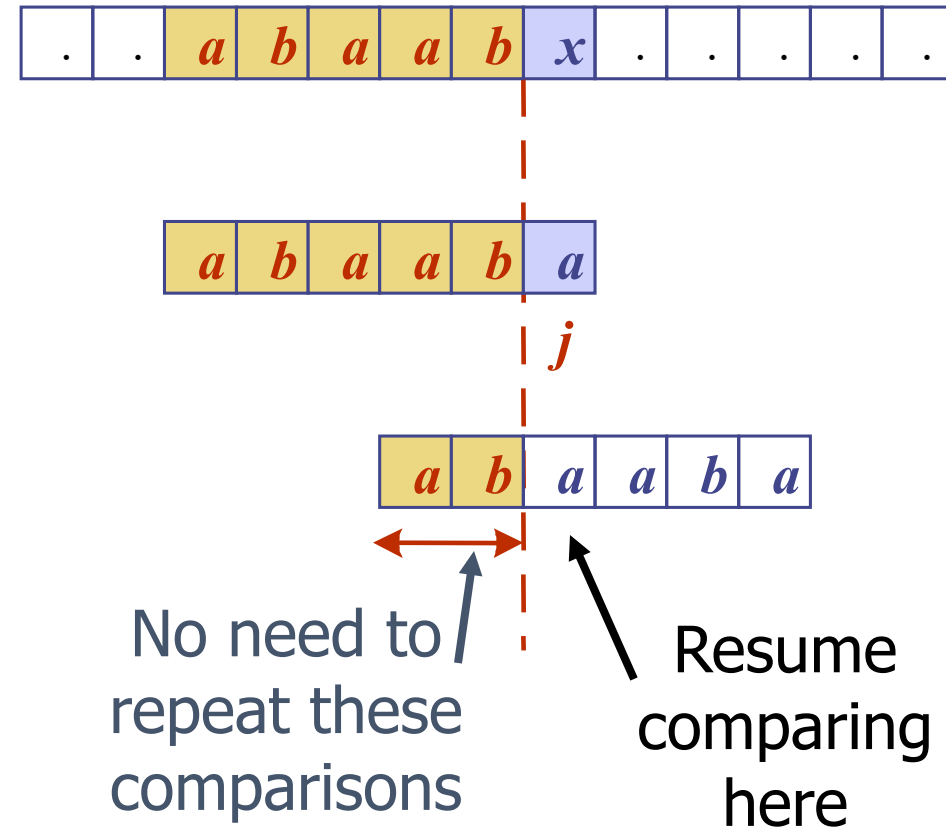
Analysis

- Boyer-Moore's algorithm runs in time $O(nm + s)$
- Example of worst case:
 - $T = aaa \dots a$
 - $P = baaa$
- The worst case may occur in images and DNA sequences but is unlikely in English text
- Boyer-Moore's algorithm is significantly faster than the brute-force algorithm on English text



The KMP Algorithm

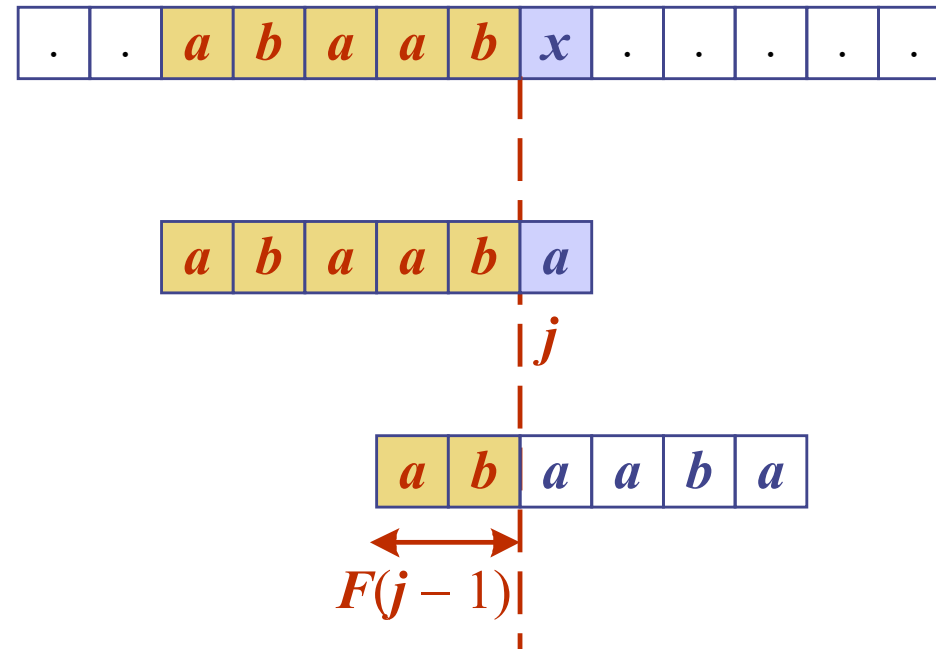
- Knuth-Morris-Pratt's algorithm compares the pattern to the text in **left-to-right**, but shifts the pattern more intelligently than the brute-force algorithm.
- When a mismatch occurs, what is the **most** we can shift the pattern so as to avoid redundant comparisons?
- Answer: the largest prefix of $P[0..j-1]$ that is a suffix of $P[1..j-1]$



KMP Failure Function

- Knuth-Morris-Pratt's algorithm preprocesses the pattern to find matches of prefixes of the pattern with the pattern itself
- The **failure function** $F(j)$ is defined as the size of the largest prefix of $P[0..j]$ that is also a suffix of $P[1..j]$
- Knuth-Morris-Pratt's algorithm modifies the brute-force algorithm so that if a mismatch occurs at $P[j] \neq T[i]$ we set $j \leftarrow F(j - 1)$

j	0	1	2	3	4	5
$P[j]$	a	b	a	a	b	a
$F(j)$	0	0	1	1	2	3



The KMP Algorithm (1/2)

Algorithm *KMPMatch*(*T*, *P*)

```
{ F = failureFunction(P);  
  i = 0;  
  j = 0;  
  while ( i < n )  
    if ( T[i] = P[j] )  
      { if ( j = m - 1 )  
        return i - j ; // match  
        else  
          { i = i + 1; j = j + 1; }  
      }  
    else  
      if ( j > 0 )  
        j = F[j - 1];  
      else  
        i = i + 1;  
  return -1; // no match  
}
```

The KMP Algorithm (2/2)

- The failure function can be represented by an array and can be computed in $O(m)$ time
- At each iteration of the while-loop, either
 - i increases by one, or the shift amount $i - j$ increases by at least one (observe that $F(j - 1) < j$)
 - Consider that the loop body is executed $2n$ times. Since the initial values of both i and j are 0, we have $i + i - j \geq 2n$ after $2n$ iterations. Therefore, $2i \geq 2n + j$ and $i \geq n + j/2$. Since j is at least 0, $i \geq n$ holds, which means the loop must terminate after $2n$ iterations.
 - Hence, there are no more than $2n$ iterations of the while-loop
- Thus, KMP's algorithm runs in optimal time $O(m + n)$

Computing the Failure Function

- The failure function can be represented by an array and can be computed in $O(m)$ time
- The construction is similar to the KMP algorithm itself
- At each iteration of the while-loop, either
 - i increases by one, or
 - the shift amount $i - j$ increases by at least one (observe that $F(j - 1) < j$)
- Hence, there are no more than $2m$ iterations of the while-loop

Algorithm *failureFunction*(P)

```
{  $F[0] = 0$ ;  
   $i = 1$ ;  
   $j = 0$ ;  
  while (  $i < m$  )  
    if (  $P[i] = P[j]$  )  
      { // we have matched  $j + 1$  char  
         $F[i] = j + 1$ ;  
         $i = i + 1$ ;  
         $j = j + 1$ ; }  
    else if (  $j > 0$  )  
      // use failure function to shift  $P$   
       $j = F[j - 1]$ ;  
    else  
      {  $F[i] = 0$ ; // no match  
         $i = i + 1$ ;  
      }  
}
```

Example

<i>a</i>	<i>b</i>	<i>a</i>	<i>c</i>	<i>a</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>c</i>	<i>c</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>c</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>a</i>	<i>b</i>	<i>b</i>
----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------

1	2	3	4	5	6
<i>a</i>	<i>b</i>	<i>a</i>	<i>c</i>	<i>a</i>	<i>b</i>

	7				
<i>a</i>	<i>b</i>	<i>a</i>	<i>c</i>	<i>a</i>	<i>b</i>

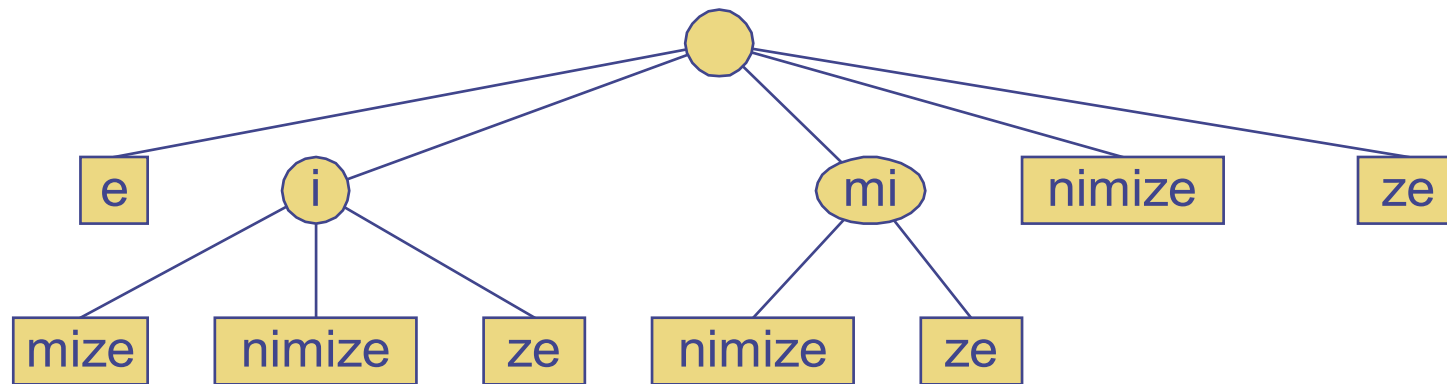
8	9	10	11	12	
<i>a</i>	<i>b</i>	<i>a</i>	<i>c</i>	<i>a</i>	<i>b</i>

	13				
<i>a</i>	<i>b</i>	<i>a</i>	<i>c</i>	<i>a</i>	<i>b</i>

	14	15	16	17	18	19
	<i>a</i>	<i>b</i>	<i>a</i>	<i>c</i>	<i>a</i>	<i>b</i>

<i>j</i>	0	1	2	3	4	5
<i>P[j]</i>	<i>a</i>	<i>b</i>	<i>a</i>	<i>c</i>	<i>a</i>	<i>b</i>
<i>F(j)</i>	0	0	1	0	1	2

Tries

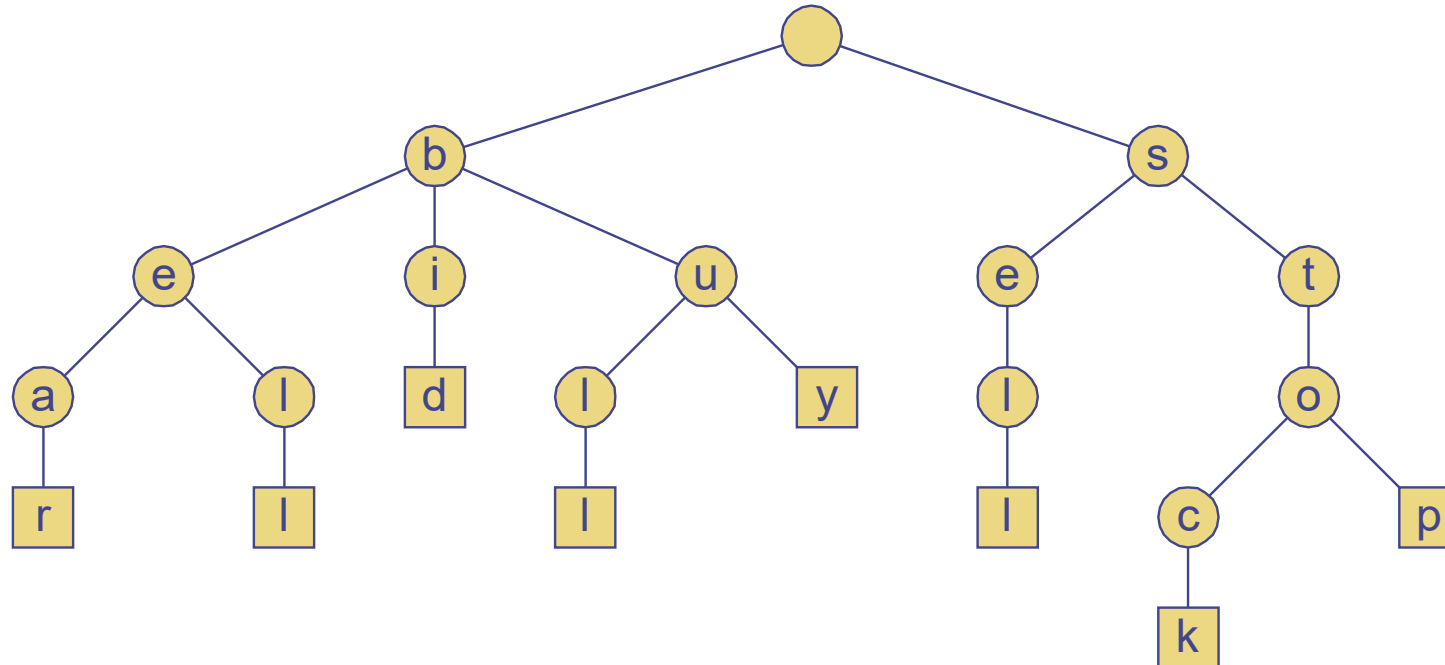


Preprocessing Strings

- Preprocessing the pattern speeds up pattern matching queries
 - After preprocessing the pattern, KMP's algorithm performs pattern matching in time proportional to the text size
- If the text is large, immutable and searched for often (e.g., works by Shakespeare), we may want to preprocess the text instead of the pattern
- A trie is a compact data structure for representing a set of strings, such as all the words in a text
 - A trie supports pattern matching queries in time proportional to the pattern size

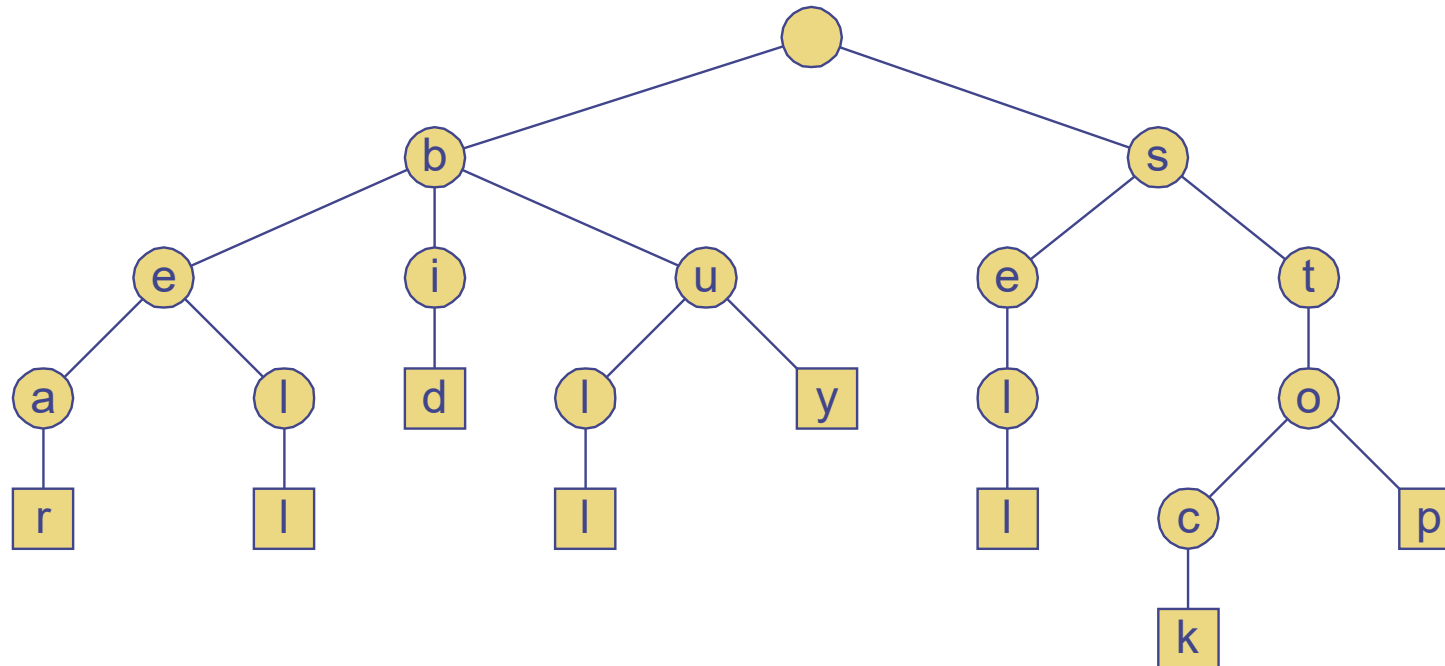
Standard Tries

- The standard trie for a set of strings S is an ordered tree such that:
 - Each node but the root is labeled with a character
 - The children of a node are alphabetically ordered
 - The paths from the external nodes to the root yield the strings of S
- Example: standard trie for the set of strings
 $S = \{ \text{bear, bell, bid, bull, buy, sell, stock, stop} \}$



Analysis of Standard Tries

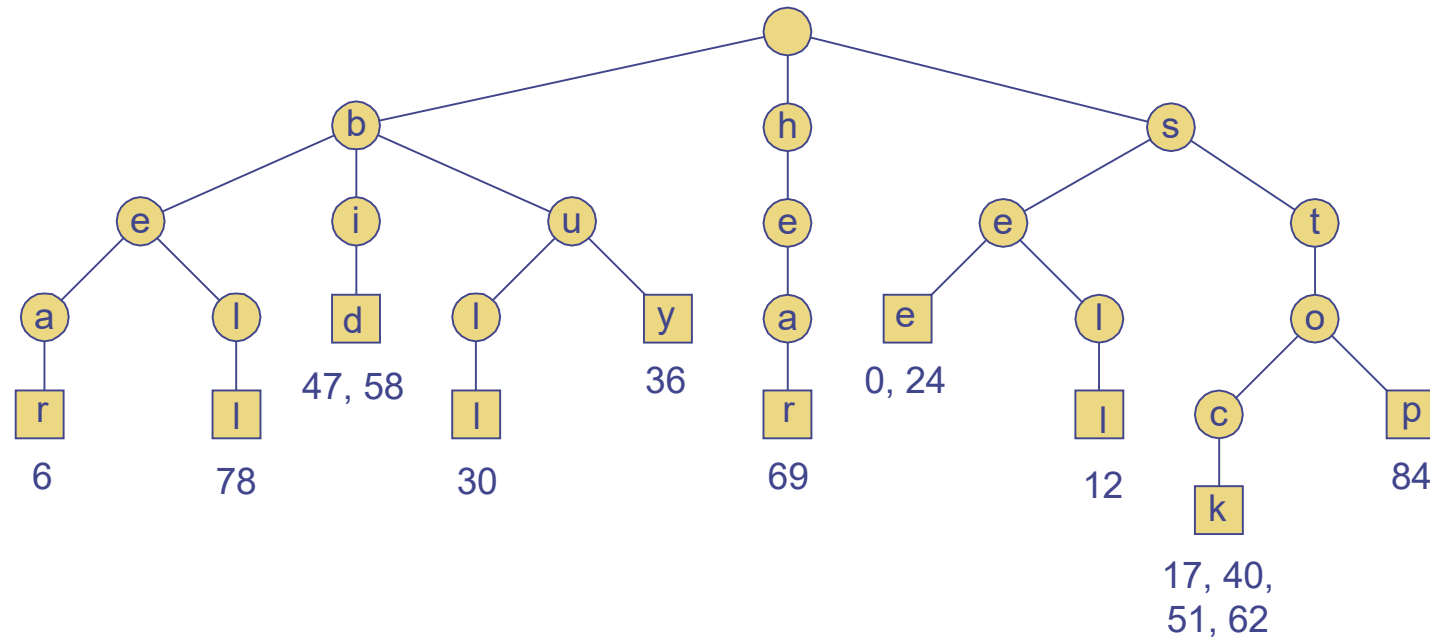
- A standard trie uses $O(n)$ space and supports searches, insertions and deletions in time $O(dm)$, where:
 - n total size of the strings in S
 - m size of the string parameter of the operation
 - d size of the alphabet



Word Matching with a Trie

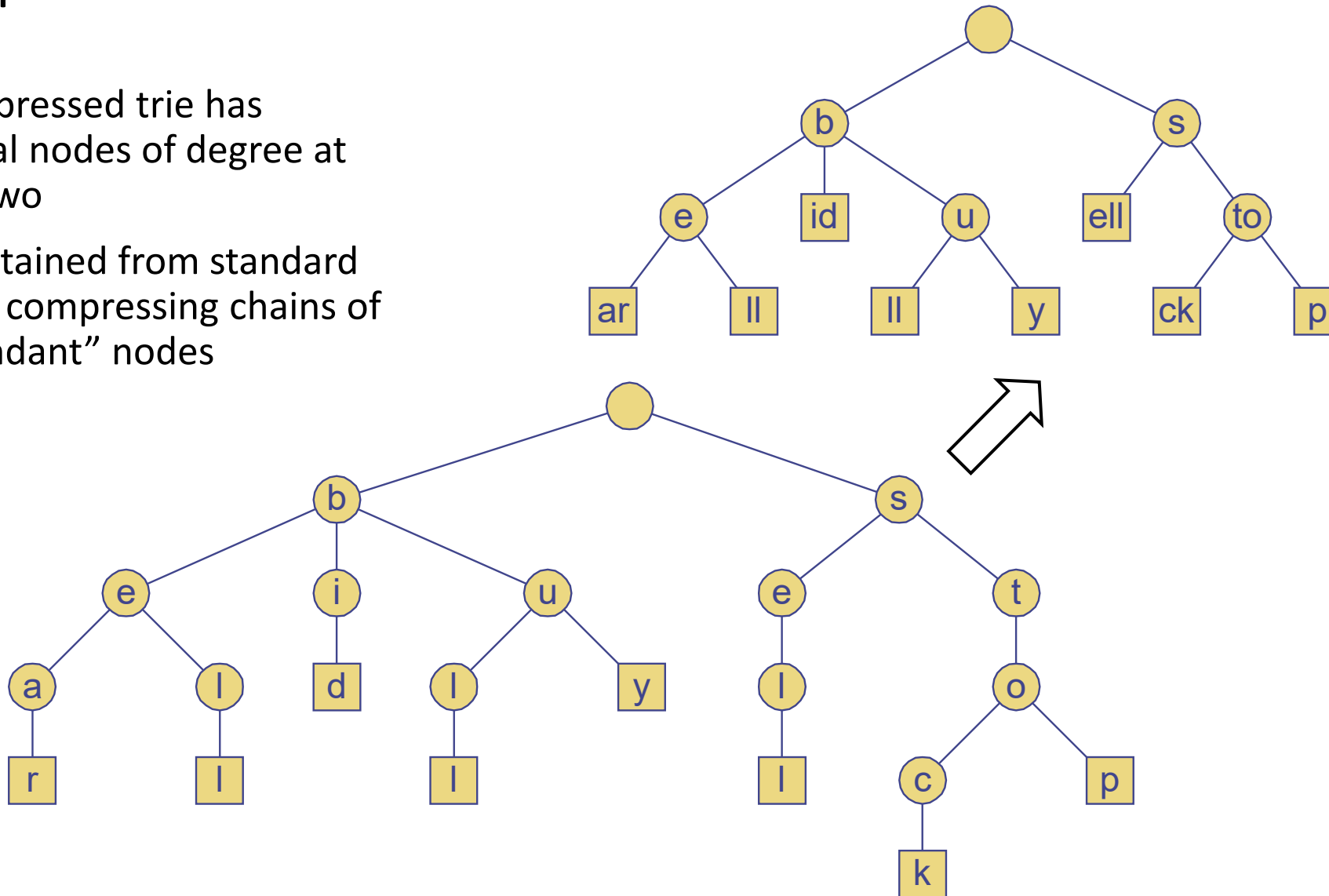
- We insert the words of the text into a trie
- Each leaf stores the occurrences of the associated word in the text

s	e	e		a		b	e	a	r	?		s	e	l	l		s	t	o	c	k	!	
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
s	e	e		a		b	u	l	l	?		b	u	y		s	t	o	c	k	!		
24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	
b	i	d		s	t	o	c	k	!		b	i	d		s	t	o	c	k	!			
47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68		
h	e	a	r		t	h	e		b	e	l	l	?		s	t	o	p	!				
69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88				



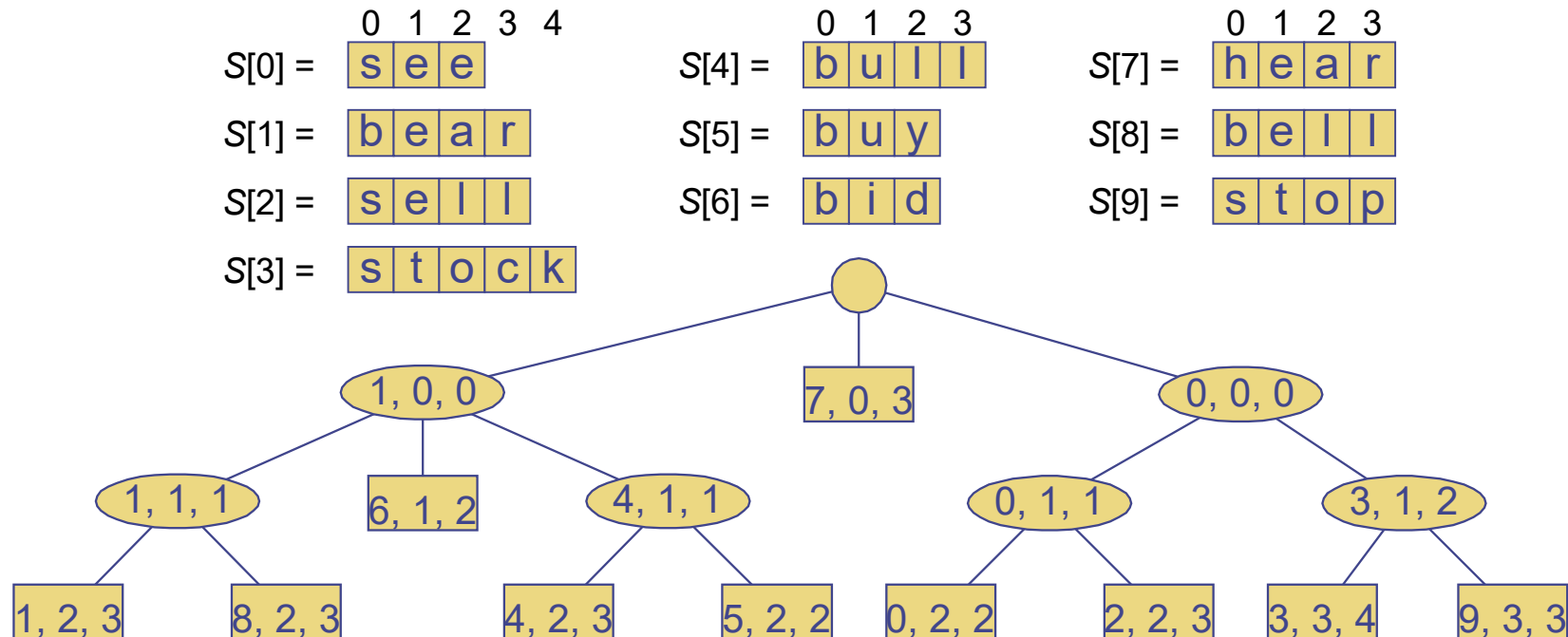
Compressed Tries

- A compressed trie has internal nodes of degree at least two
- It is obtained from standard trie by compressing chains of “redundant” nodes



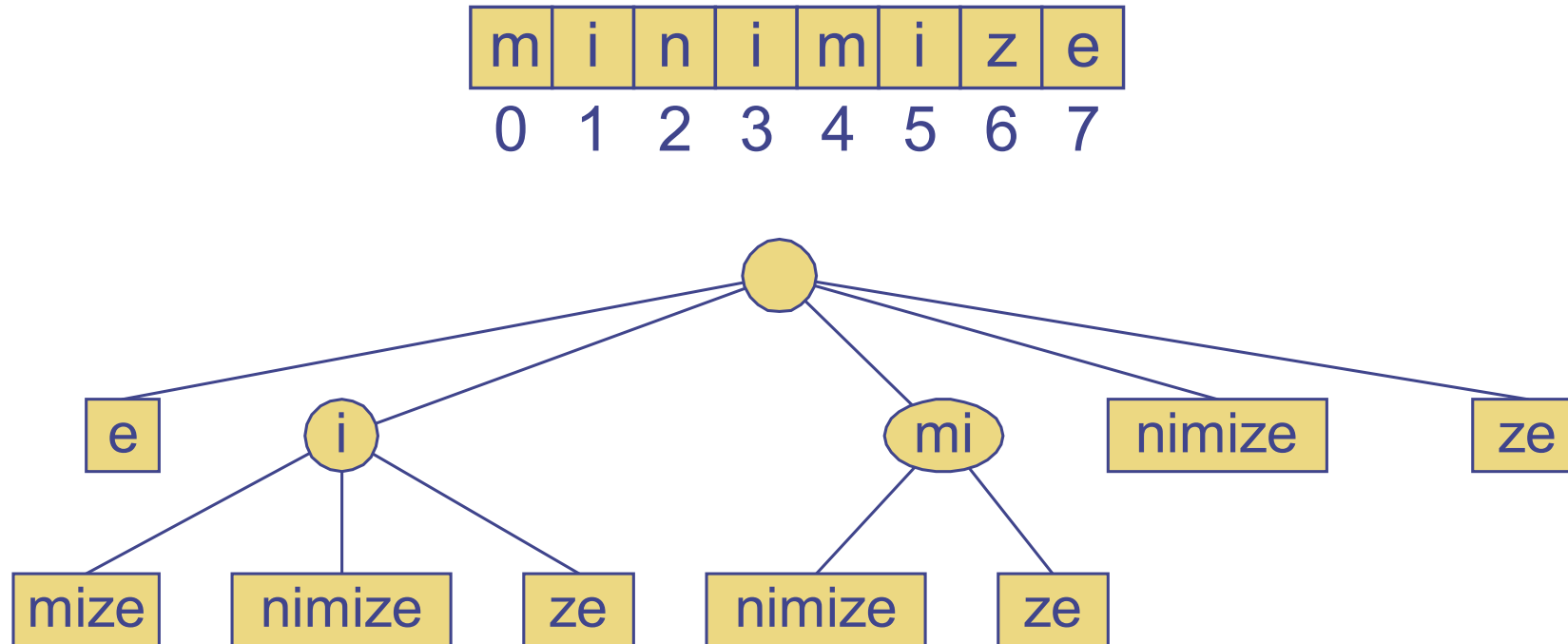
Compact Representation

- Compact representation of a compressed trie for an array of strings:
 - Stores at the nodes ranges of indices instead of substrings
 - Uses $O(s)$ space, where s is the number of strings in the array
 - Serves as an auxiliary index structure



Suffix Trie

- The suffix trie of a string X is the compressed trie of all the suffixes of X



Pattern Matching Using Suffix Trie

(1/2)

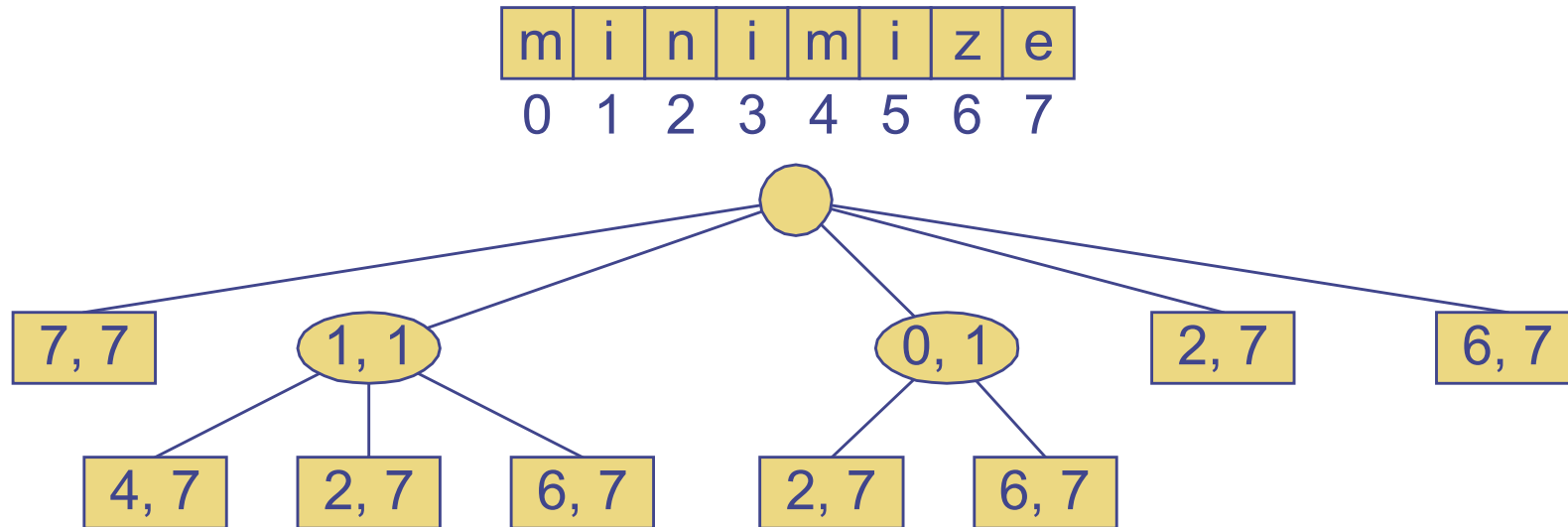
```
Algorithm suffixTrieMatch(T, P)
{ p = P.length; j = 0; v = T.root();
  repeat
    { for each child w of v do
      { // we have matched j + 1 char
        childTraversed=false; i = start(w); // start(w) is the start index of w
        if ( P[j] = X[i] ) // process child w
          { childTraversed=true;
            x = end(w) - i + 1; // end(w) is the end index of w
            if ( p ≤ x )
              // suffix is shorter than or of the same length of the node label
              { if ( P[j:j+p-1] = X[i:i+p-1] ) return i - j;
                else return “P is not a substring of X”; }
            else // the pattern goes beyond the substring stored at w
              { if ( P[j:j+x-1] = X[i:i+x-1] )
                  { p = p - x; // update suffix length
                    j = j + x; // update suffix start index
                    v = w; break ; }
                  else return “P is not a substring of X”; } } } }
        until childTraversed=false or T.isExternal(v);
      return “P is not a substring of X”; }
```

Pattern Matching Using Suffix Trie (2/2)

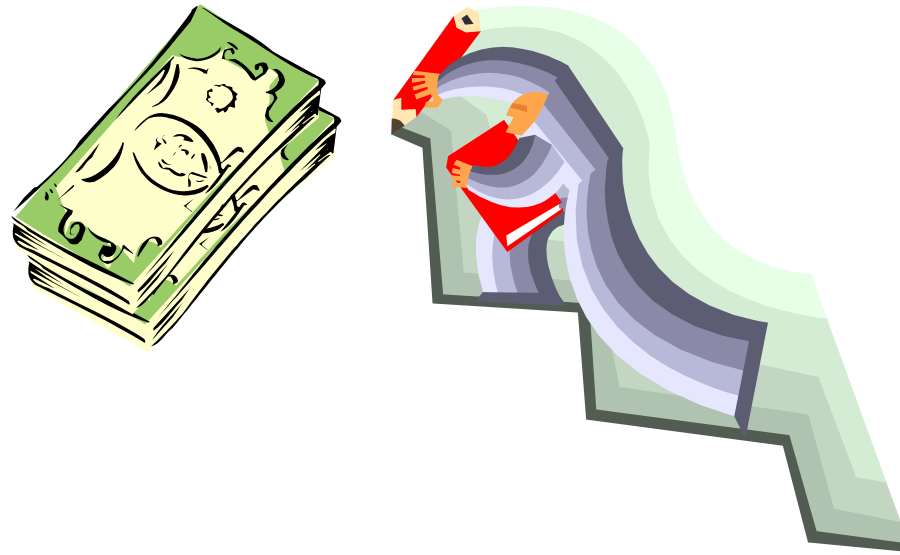
- Input of the algorithm:
 - Compact suffix trie T for a text X and pattern P .
- Output of the algorithm:
 - Starting index of a substring of X matching P or an indication that P is not a substring.
- The algorithm assumes the following additional property on the labels of the nodes in the compact representation of the suffix trie:
 - If node v has label (i, j) and Y is the string of length y associated with the path from the root to v (included), then $X[j-y+1..j]=Y$.
- This property ensures that we can easily compute the start index of the pattern in the text when a match occurs.

Analysis of Suffix Tries

- Compact representation of the suffix trie for a string X of size n from an alphabet of size d
 - Uses $O(n)$ space
 - Supports arbitrary pattern matching queries in X in $O(dm)$ time, where m is the size of the pattern
 - Can be constructed in $O(n)$ time



Greedy Method and Text Compression



The Greedy Method Technique

- **The greedy method** is a general algorithm design paradigm, built on the following elements:
 - **configurations**: different choices, collections, or values to find
 - **objective function**: a score assigned to configurations, which we want to either maximize or minimize
- It works best when applied to problems with the **greedy-choice** property:
 - a globally-optimal solution can always be found by a series of local improvements from a starting configuration.

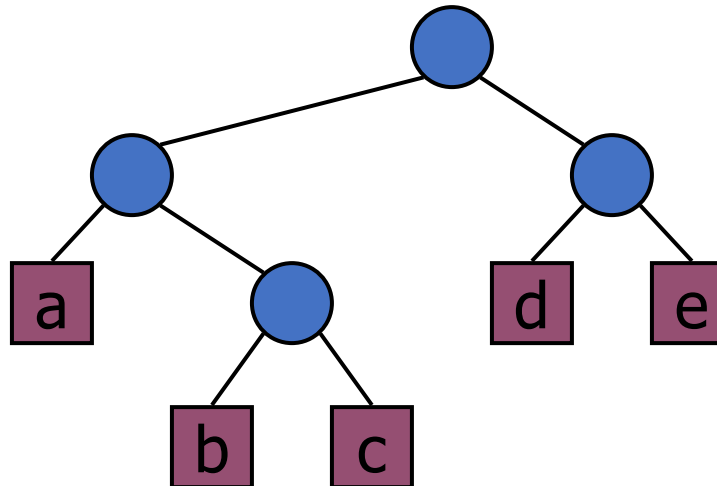
Text Compression

- Given a string X , efficiently encode X into a smaller string Y
 - Saves memory and/or bandwidth
- A good approach: **Huffman encoding**
 - Compute frequency $f(c)$ for each character c .
 - Encode high-frequency characters with short code words
 - No code word is a prefix for another code
 - Use an optimal encoding tree to determine the code words

Encoding Tree Example

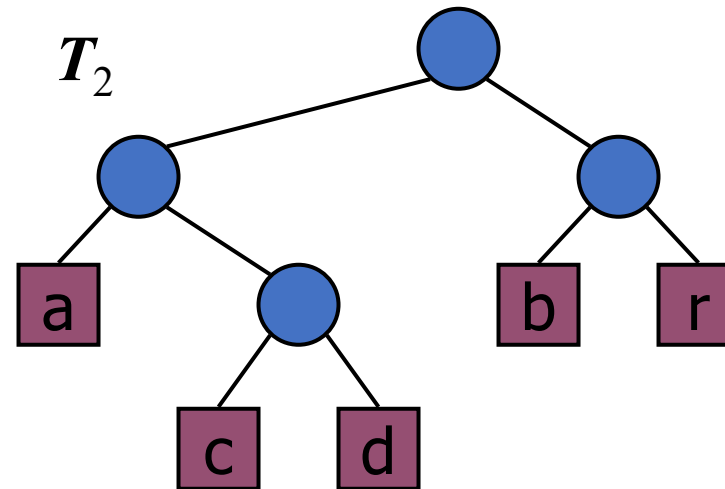
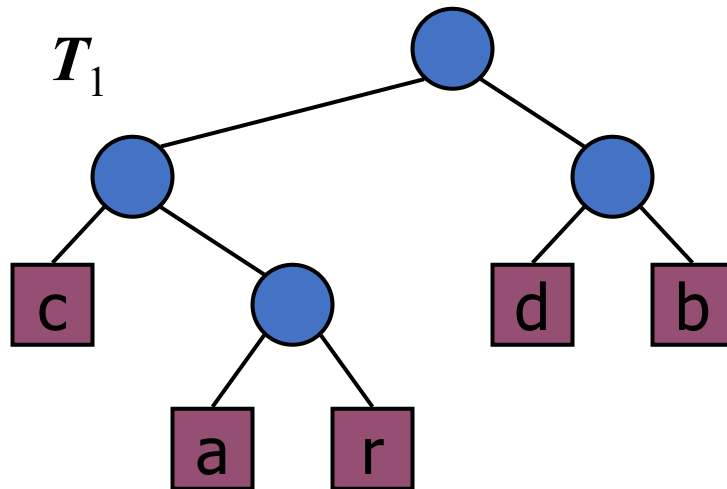
- A **code** is a mapping of each character of an alphabet to a binary code-word
- A **prefix code** is a binary code such that no code-word is the prefix of another code-word
- An **encoding tree** represents a prefix code
 - Each external node stores a character
 - The code word of a character is given by the path from the root to the external node storing the character (0 for a left child and 1 for a right child)

00	010	011	10	11
a	b	c	d	e



Encoding Tree Optimization

- Given a text string X , we want to find a prefix code for the characters of X that yields a small encoding for X
 - Frequent characters should have short code-words
 - Rare characters should have long code-words
- Example
 - $X = \text{abracadabra}$
 - T_1 encodes X into 29 bits
 - T_2 encodes X into 24 bits



Huffman's Algorithm

- Given a string X , Huffman's algorithm construct a prefix code the minimizes the size of the encoding of X
- It runs in time $O(n + d \log d)$, where n is the size of X and d is the number of distinct characters of X
- A heap-based priority queue is used as an auxiliary structure

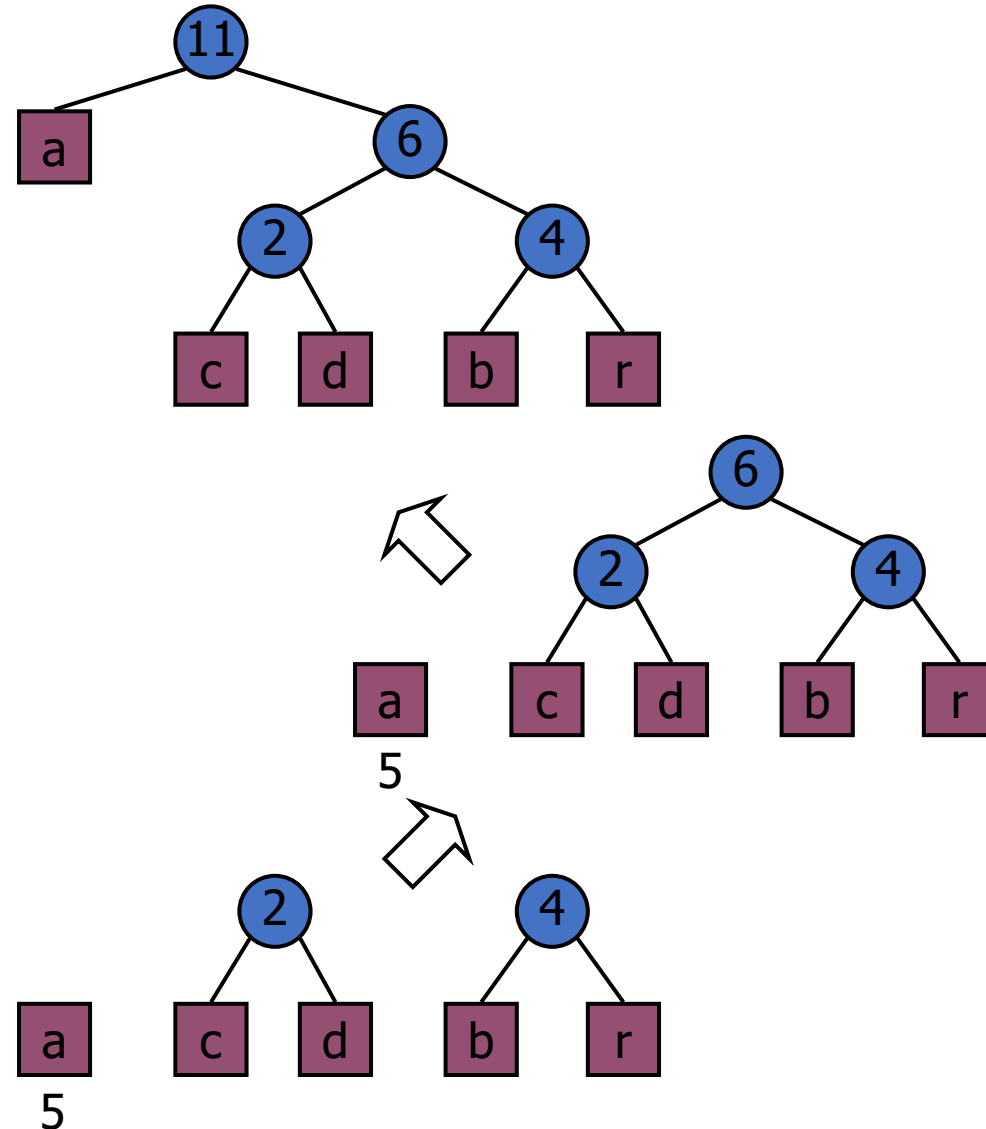
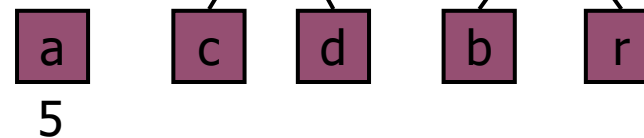
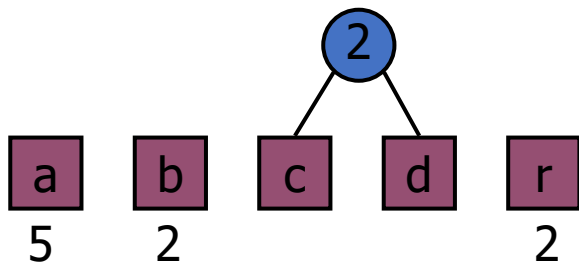
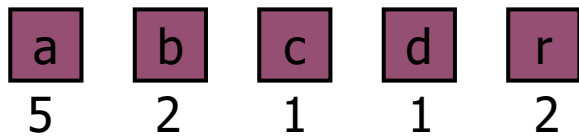
```
Algorithm HuffmanEncoding( $X$ )
  Input string  $X$  of size  $n$ 
  Output optimal encoding trie for  $X$ 
{
   $C = \text{distinctCharacters}(X)$ ;
  computeFrequencies( $C, X$ );
   $Q = \text{new empty heap}$ ;
  for all  $c \in C$ 
    {  $T = \text{new single-node tree storing } c$ ;
       $Q.\text{insert}(\text{getFrequency}(c), T)$ ; }
  while (  $Q.\text{size()} > 1$  )
    {  $f_1 = Q.\text{minKey}()$ ;
       $T_1 = Q.\text{removeMin}()$ ;
       $f_2 = Q.\text{minKey}()$ ;
       $T_2 = Q.\text{removeMin}()$ ;
       $T = \text{join}(T_1, T_2)$ ;
       $Q.\text{insert}(f_1 + f_2, T)$ ;
    }
  return  $Q.\text{removeMin}()$ ;
}
```

Example

$X = \text{abracadabra}$

Frequencies

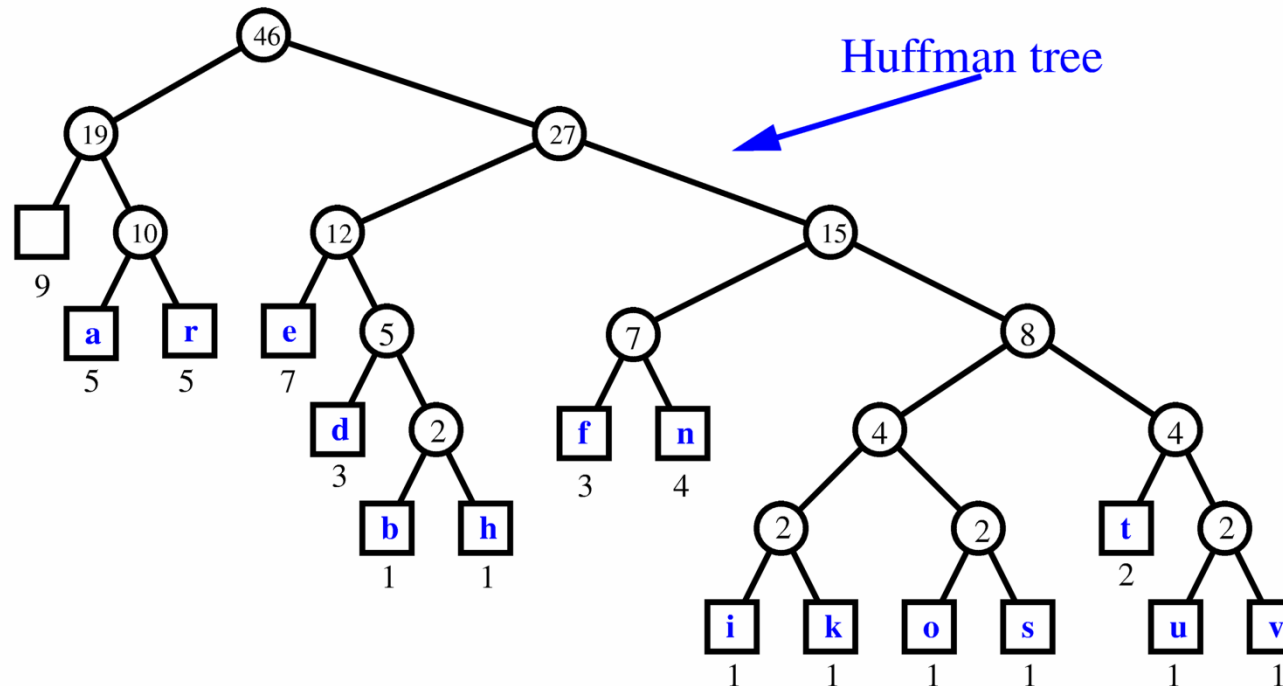
a	b	c	d	r
5	2	1	1	2



Extended Huffman Tree Example

String: **a fast runner need never be afraid of the dark**

Character		a	b	d	e	f	h	i	k	n	o	r	s	t	u	v
Frequency	9	5	1	3	7	3	1	1	1	4	1	5	1	2	1	1



The Fractional Knapsack Problem






- Given: A set S of n items, with each item i having
 - b_i - a positive benefit
 - w_i - a positive weight
- Goal: Choose items with maximum total benefit but with weight at most W .
- If we are allowed to take fractional amounts, then this is the **fractional knapsack problem**.
 - In this case, we let x_i denote the amount we take of item i

- Objective: maximize
$$\sum_{i \in S} b_i (x_i / w_i)$$

- Constraint:
$$\sum_{i \in S} x_i \leq W$$

Example

- Given: A set S of n items, with each item i having
 - b_i - a positive benefit
 - w_i - a positive weight
- Goal: Choose items with maximum total benefit but with weight at most W .

Items:					
	1	2	3	4	5
Weight:	4 ml	8 ml	2 ml	6 ml	1 ml
Benefit:	\$12	\$32	\$40	\$30	\$50
Value: (\$ per ml)	3	4	20	5	50



"knapsack"

Solution:

- 1 ml of 5
- 2 ml of 3
- 6 ml of 4
- 1 ml of 2

10 ml

The Fractional Knapsack Algorithm

- Greedy choice: Keep taking item with highest **value** (benefit to weight ratio)
 - Since $\sum_{i \in S} b_i (x_i / w_i) = \sum_{i \in S} (b_i / w_i) x_i$
 - Run time: $O(n \log n)$. Why?
- Correctness: Suppose there is a better solution
 - there is an item i with higher value than a chosen item j , but $x_i < w_i$, $x_j > 0$ and $v_i < v_j$
 - If we substitute some i with j , we get a better solution
 - How much of i : $\min\{w_i - x_i, x_j\}$
 - Thus, there is no better solution than the greedy one

Algorithm *fractionalKnapsack*(S, W)

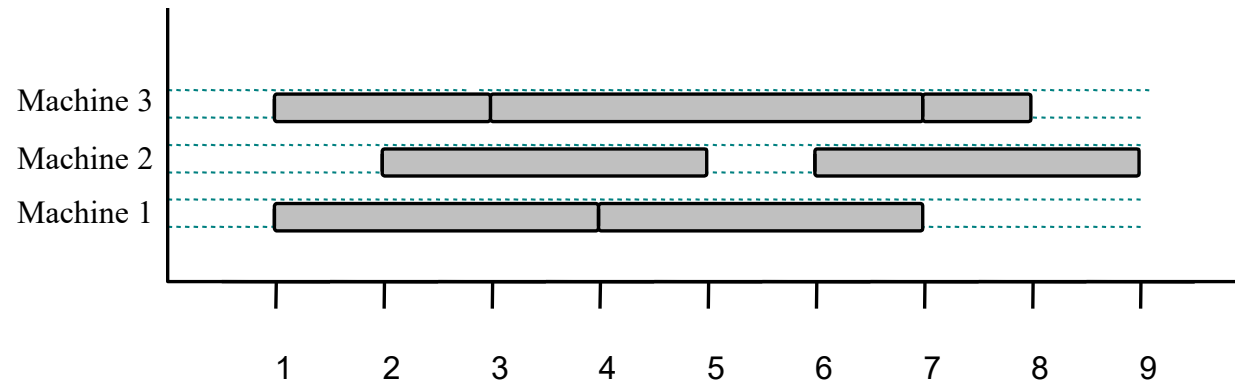
Input: set S of items with benefit b_i and weight w_i ; max. weight W

Output: amount x_i of each item i to maximize benefit with weight at most W

```
{ for each item i in S
  {  $x_i = 0$ ;
     $v_i = b_i / w_i$ ; // value
  }
 $w = 0$ ; // total weight
while (  $w < W$  )
  { remove item i with highest  $v_i$ 
     $x_i = \min\{w_i, W - w\}$ ;
     $w = w + \min\{w_i, W - w\}$ ;
  }
}
```

Task Scheduling

- Given: a set T of n tasks, each having:
 - A start time, s_i
 - A finish time, f_i (where $s_i < f_i$)
- Goal: Perform all the tasks using a minimum number of “machines.”



Task Scheduling Algorithm

- Greedy choice: consider tasks by their start time and use as few machines as possible with this order.
 - Run time: $O(n \log n)$. Why?
- Correctness: Suppose there is a better schedule.
 - We can use $k-1$ machines
 - The algorithm uses k
 - Let i be first task scheduled on machine k
 - Machine i must conflict with $k-1$ other tasks
 - But that means there is no non-conflicting schedule using $k-1$ machines

Algorithm *taskSchedule(T)*

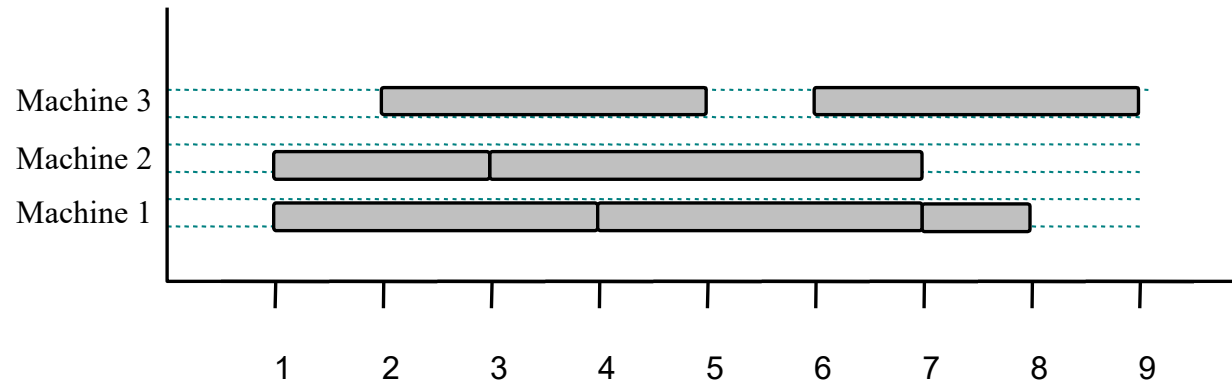
Input: set T of tasks with start time s_i and finish time f_i

Output: non-conflicting schedule with minimum number of machines

```
{  $m = 0$ ; // no. of machines
while  $T$  is not empty
{ remove task  $i$  with smallest  $s_i$ 
  if there's a machine  $j$  for  $i$  then
    schedule  $i$  on machine  $j$ ;
  else
    {  $m = m + 1$ ;
      schedule  $i$  on machine  $m$ ;
    }
}
```


Example

- Given: a set T of n tasks, each having:
 - A start time, s_i
 - A finish time, f_i (where $s_i < f_i$)
 - $[1,4], [1,3], [2,5], [3,7], [4,7], [6,9], [7,8]$ (ordered by start)
- Goal: Perform all tasks on min. number of machines



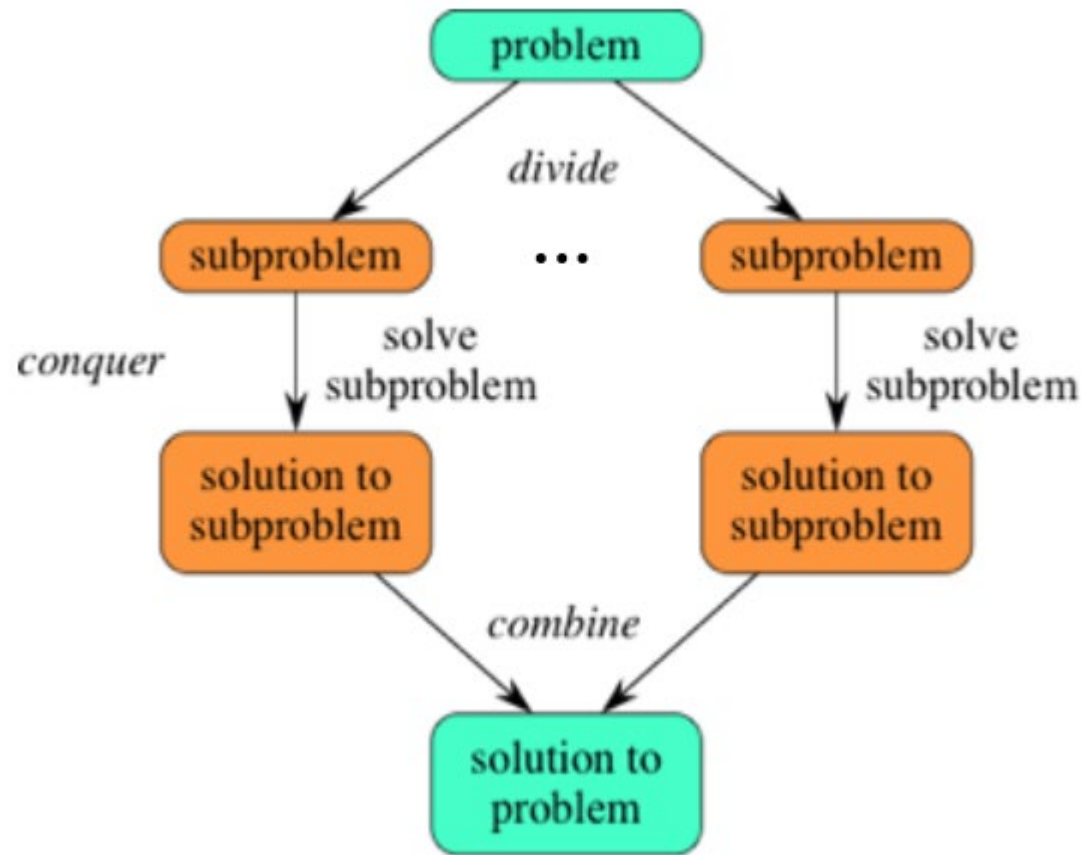
Dynamic Programming



Divide and Conquer (1/2)

- A problem-solving strategy in computer science
- Basic idea:
 - Decompose a given problem into one or more subproblems
 - Solve the subproblems in turn
 - Combine the solutions to the subproblems into the solution to the given problem.
- If subproblems are of the same structures as the given problem, we can use recursion to solve the given problem

Divide and Conquer (2/2)



Taken from
<https://tellingthetruth1993.com/2018/03/02/the-divide-and-conquer-club/>

Key Ideas with Dynamic Programming (1/2)

- When applying recursion to solve a problem, if subproblems do not overlap, recursions will be efficient. Otherwise, recursions may lead to exponential time complexity (recall the recursive function for Fibonacci numbers)
- When subproblems overlap, we find an optimal way for solving the problem to eliminate redundant computation
 - Solve all the problems (smallest problems) at the lowest level, and proceed to solve all the subproblems at the next level until the given problem is solved.

Key Ideas with Dynamic Programming (2/2)

Algorithm BinaryFib(k)

{ Input : Nonnegative integer k

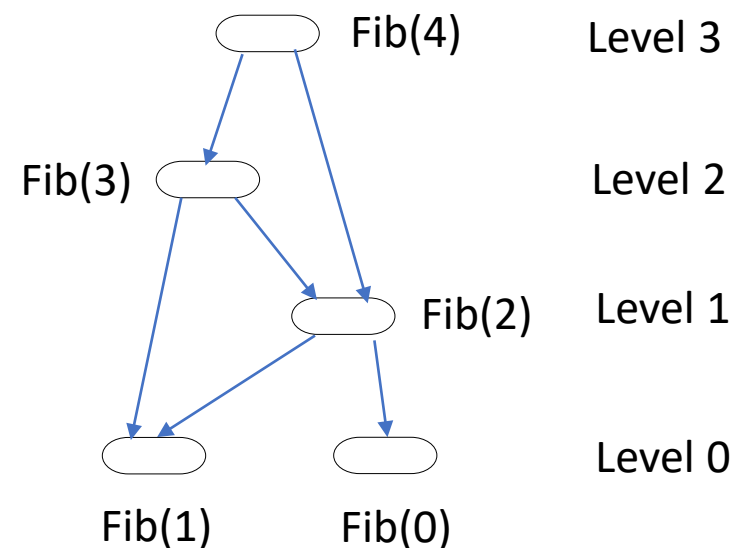
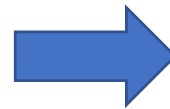
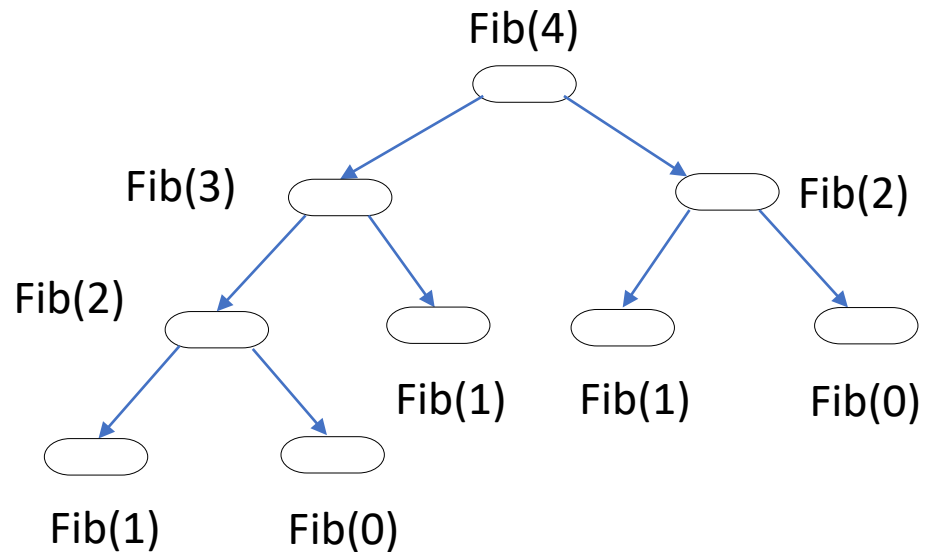
Output : The kth Fibonacci number F_k

if (k = 0 or 1) return k;

else

return BinaryFib(k - 1) + BinaryFib(k - 2);

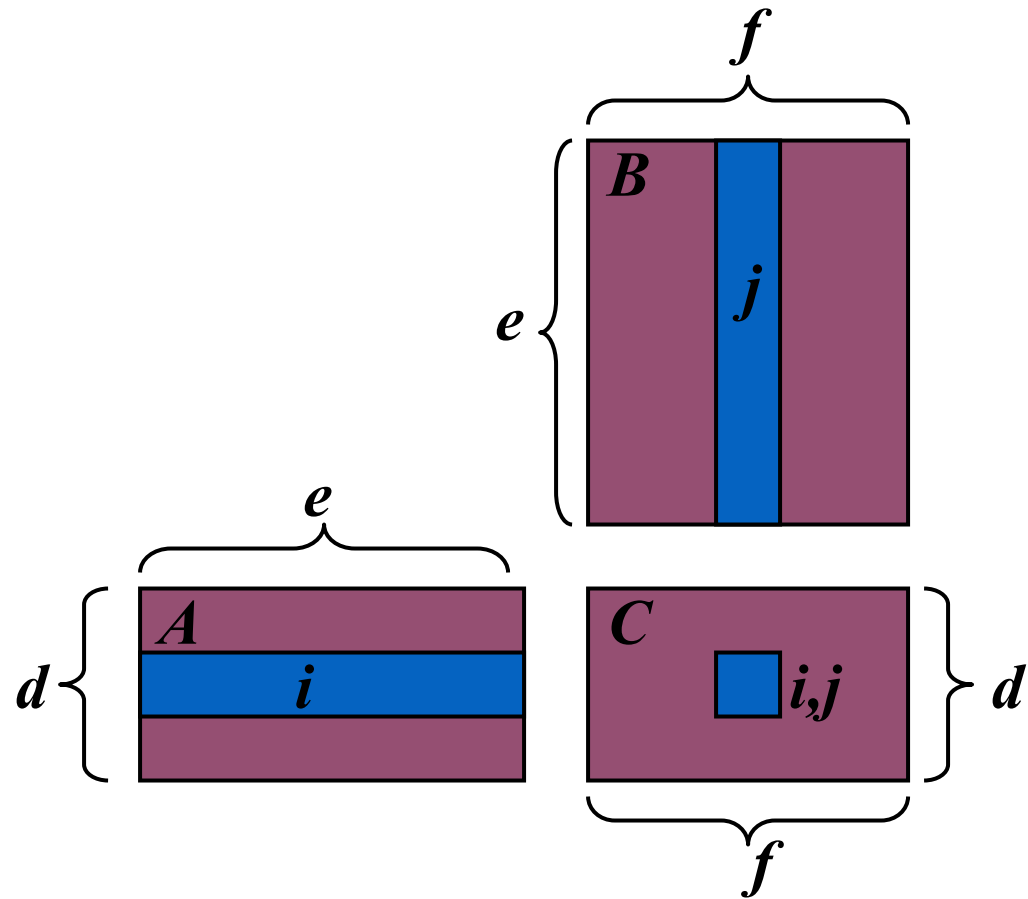
}



Matrix Chain-Products

- Review: Matrix Multiplication.
 - $C = A * B$
 - A is $d \times e$ and B is $e \times f$
 - $O(def)$ time

$$C[i, j] = \sum_{k=0}^{e-1} A[i, k] * B[k, j]$$



Matrix Chain-Products

- **Matrix Chain-Product:**

- Compute $A = A_0 * A_1 * \dots * A_{n-1}$
- A_i is $d_i \times d_{i+1}$
- Problem: How to parenthesize?

- Example

- B is 3×100
- C is 100×5
- D is 5×5
- $(B * C) * D$ takes $1500 + 75 = 1575$ ops
- $B * (C * D)$ takes $1500 + 2500 = 4000$ ops

An Enumeration Approach

- **Matrix Chain-Product Alg.:**

- Try all possible ways to parenthesize $A=A_0 * A_1 * \dots * A_{n-1}$
- Calculate number of ops for each one
- Pick the one that is best

- Running time:

- The number of parenthesizations is equal to the number of binary trees with n nodes
- This is **exponential!**
- It is called the Catalan number, and it is almost 4^n .
- This is a terrible algorithm!

A Greedy Approach

- Idea #1: repeatedly select the product that uses (up) the most operations.
- Counter-example:
 - A is 10×5
 - B is 5×10
 - C is 10×5
 - D is 5×10
 - Greedy idea #1 gives $(A*B)*(C*D)$, which takes $500+1000+500 = 2000$ ops
 - $A*((B*C)*D)$ takes $500+250+250 = 1000$ ops

Another Greedy Approach

- Idea #2: repeatedly select the product that uses the fewest operations.
- Counter-example:
 - A is 101×11
 - B is 11×9
 - C is 9×100
 - D is 100×99
 - Greedy idea #2 gives $A*((B*C)*D)$, which takes $109989+9900+108900=228789$ ops
 - $(A*B)*(C*D)$ takes $9999+89991+89100=189090$ ops
- The greedy approach is not giving us the optimal value.

A “Recursive” Approach

- Define **subproblems**:
 - Find the best parenthesization of $A_i * A_{i+1} * \dots * A_j$.
 - Let $N_{i,j}$ denote the number of operations done by this subproblem.
 - The optimal solution for the whole problem is $N_{0,n-1}$.
- **Subproblem optimality**: The optimal solution can be defined in terms of optimal subproblems
 - There has to be a final multiplication (root of the expression tree) for the optimal solution.
 - Say, the final multiply is at index i : $(A_0 * \dots * A_i) * (A_{i+1} * \dots * A_{n-1})$.
 - Then the optimal solution $N_{0,n-1}$ is the sum of two optimal subproblems, $N_{0,i}$ and $N_{i+1,n-1}$ plus the time for the last multiply.
 - If the global optimum did not have these optimal subproblems, we could define an even better “optimal” solution.

A Characterizing Equation

- The global optimal has to be defined in terms of optimal subproblems, depending on where the final multiply is at.
- Let us consider all possible places for that final multiply:
 - Recall that A_i is a $d_i \times d_{i+1}$ dimensional matrix.
 - So, a characterizing equation for $N_{i,j}$ is the following:

$$N_{i,j} = \min_{i \leq k < j} \{N_{i,k} + N_{k+1,j} + d_i d_{k+1} d_{j+1}\}$$

- Note that subproblems are not independent--the **subproblems overlap**.

A Dynamic Programming Algorithm

- Since subproblems overlap, we don't use recursion.
- Instead, we construct optimal subproblems "bottom-up."
- $N_{i,i}$'s are easy, so start with them
- Then do length 2,3,... subproblems, and so on.
- Running time: $O(n^3)$

Algorithm *matrixChain(S)*:

Input: sequence S of n matrices to be multiplied

Output: number of operations in an optimal parenthesization of S

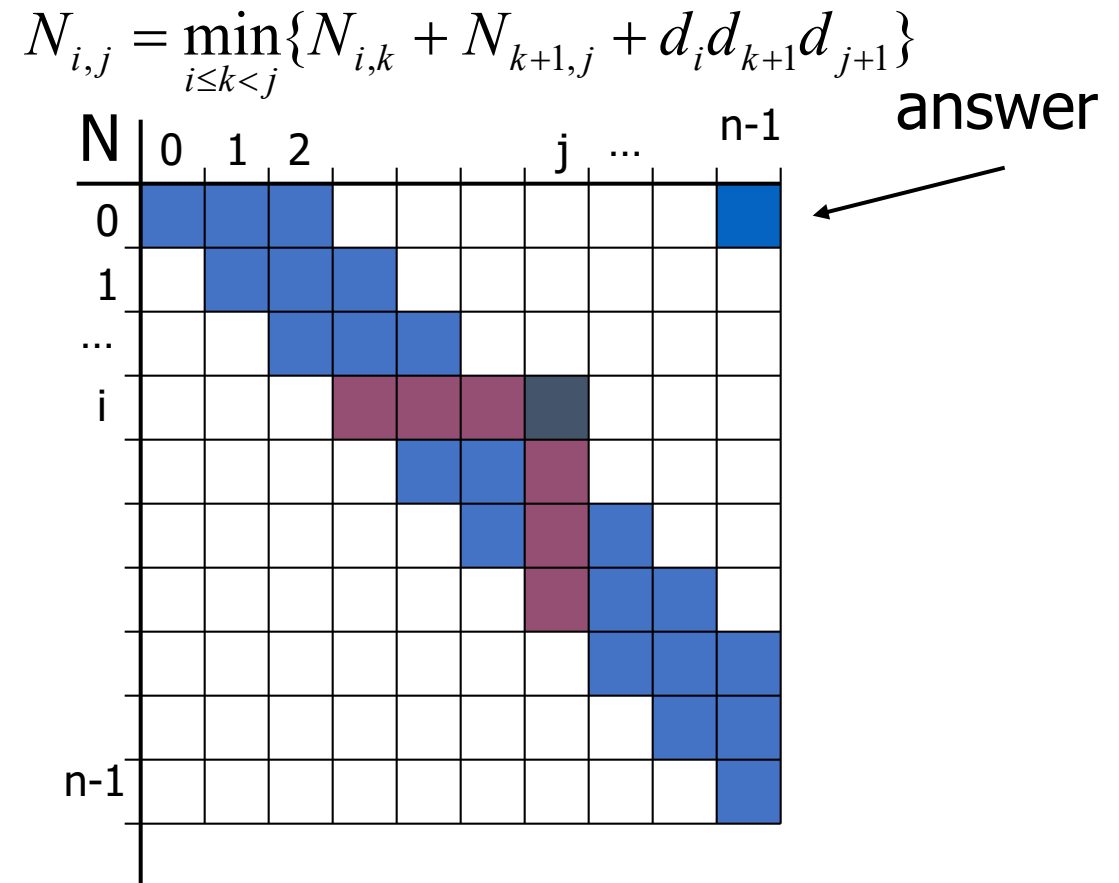
```

{ for (  $i = 1$ ;  $i \leq n-1$ ;  $i++$  )
     $N_{i,i} = 0$ ;
    for (  $b = 1$ ;  $b \leq n-1$ ;  $b++$  )
        for (  $i = 0$ ;  $i \leq n-b-1$ ;  $i++$  )
            {  $j = i+b$ ;
               $N_{i,j} = +\text{infinity}$ ;
              for (  $k = i$ ;  $k \leq j-1$ ;  $k++$  )
                   $N_{i,j} = \min\{N_{i,j}, N_{i,k} + N_{k+1,j} + d_i d_{k+1}$ 
                     $d_{j+1}\}$ ;
            }
    }
}

```

A Dynamic Programming Algorithm Visualization

- The bottom-up construction fills in the N array by diagonals
- $N_{i,j}$ gets values from pervious entries in i-th row and j-th column
- Filling in each entry in the N table takes $O(n)$ time.
- Total running time: $O(n^3)$
- Getting actual parenthesization can be done by remembering “k” for each N entry



The General Dynamic Programming Technique

- Applies to a problem that at first seems to require a lot of time (possibly exponential), provided we have:
 - **Simple subproblems:** the subproblems can be defined in terms of a few variables, such as j , k , l , m , and so on.
 - **Subproblem optimality:** the global optimum value can be defined in terms of optimal subproblems
 - **Subproblem overlap:** the subproblems are not independent, but instead they overlap (hence, should be constructed bottom-up).

Subsequences

- A ***subsequence*** of a character string $x_0x_1x_2\dots x_{n-1}$ is a string of the form $x_{i_1}x_{i_2}\dots x_{i_k}$, where $i_j < i_{j+1}$.
- Not the same as substring!
- Example String: ABCDEFGHIJK
 - Subsequence: ACEGIJK
 - Subsequence: DFGHK
 - Not subsequence: DAGH

The Longest Common Subsequence (LCS) Problem

- Given two strings X and Y , the longest common subsequence (LCS) problem is to find a longest subsequence common to both X and Y
- Has applications to DNA similarity testing (alphabet is $\{A, C, G, T\}$)
- Example: ABCDEFG and XZACKDFWGH have ACDFG as a longest common subsequence

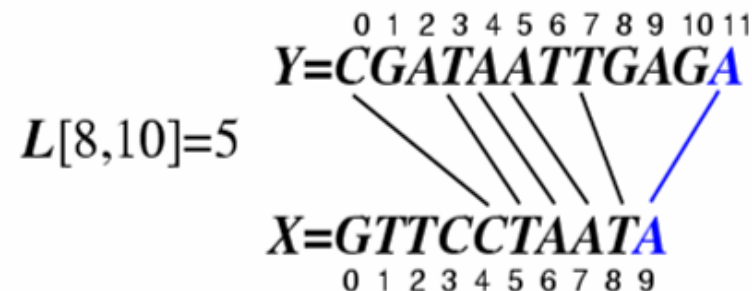
A Poor Approach to the LCS Problem

- A Brute-force solution:
 - Enumerate all subsequences of X
 - Test which ones are also subsequences of Y
 - Pick the longest one.
- Analysis:
 - If X is of length n , then it has 2^n subsequences
 - This is an exponential-time algorithm!

A Dynamic-Programming Approach to the LCS Problem

- Define $L[i,j]$ to be the length of the longest common subsequence of $X[0..i]$ and $Y[0..j]$.
- Allow for -1 as an index, so $L[-1,k] = 0$ and $L[k,-1]=0$, to indicate that the null part of X or Y has no match with the other.
- Then we can define $L[i,j]$ in the general case as follows:
 1. If $x_i=y_j$, then $L[i,j] = L[i-1,j-1] + 1$ (we can add this match)
 2. If $x_i \neq y_j$, then $L[i,j] = \max\{L[i-1,j], L[i,j-1]\}$ (we have no match here)

Case 1:



Case 2:



An LCS Algorithm

Algorithm LCS(X, Y):

Input: Strings X and Y with n and m elements, respectively

Output: For $i = 0, \dots, n-1, j = 0, \dots, m-1$, the length $L[i, j]$ of a longest string that is a subsequence of both the string $X[0..i] = x_0x_1x_2\dots x_i$ and the string $Y[0..j] = y_0y_1y_2\dots y_j$

```
{ for ( i = -1; i ≤ n-1, i ++ )  
    L[i, -1] = 0;  
  for ( j = -1; j ≤ m-1, j ++ )  
    L[-1, j] = 0;  
  for ( i = 0; i ≤ n-1, i ++ )  
    for ( j = 0; j ≤ m-1, j ++ )  
      if (  $x_i = y_j$  )  
         $L[i, j] = L[i-1, j-1] + 1$ ;  
      else  
         $L[i, j] = \max\{L[i-1, j], L[i, j-1]\}$ ;  
  return array  $L$ ;  
}
```

Visualizing the LCS Algorithm

<i>L</i>	-1	0	1	2	3	4	5	6	7	8	9	10	11
-1	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	1	1	1	1	1	1	1	1	1	1
1	0	0	1	1	2	2	2	2	2	2	2	2	2
2	0	0	1	1	2	2	2	3	3	3	3	3	3
3	0	1	1	1	2	2	2	3	3	3	3	3	3
4	0	1	1	1	2	2	2	3	3	3	3	3	3
5	0	1	1	1	2	2	2	3	4	4	4	4	4
6	0	1	1	2	2	3	3	3	4	4	5	5	5
7	0	1	1	2	2	3	4	4	4	4	5	5	6
8	0	1	1	2	3	3	4	5	5	5	5	5	6
9	0	1	1	2	3	4	4	5	5	5	6	6	6

0 1 2 3 4 5 6 7 8 9 10 11
Y=CGATAATTGAGA
 0 1 2 3 4 5 6 7 8 9
X=GTTCCTAATA

Analysis of LCS Algorithm

- We have two nested loops
 - The outer one iterates n times
 - The inner one iterates m times
 - A constant amount of work is done inside each iteration of the inner loop
 - Thus, the total running time is $O(nm)$
- Answer is contained in $L[n,m]$ (and the subsequence can be recovered from the L table)

Summary

1. Boyer-Moore algorithm
2. KMP algorithm
3. Standard tries
4. Compressed tries
5. Compact representation of compressed tries
6. Greedy method
7. Dynamic programming
8. Suggested reading:
Sedgewick, Ch. 5.3, 15.2, 15.3.