# STRINGS AND PATTERN MATCHING

- Brute Force, Rabin-Karp, Knuth-Morris-Pratt

# String Searching

- The previous slide is not a great example of what is meant by “String Searching.” Nor is it meant to ridicule people without eyes....
- The object of string searching is to find the location of a specific text pattern within a larger body of text (e.g., a sentence, a paragraph, a book, etc.).
- As with most algorithms, the main considerations for string searching are speed and efficiency.
- There are a number of string searching algorithms in existence today, but the two we shall review are Brute Force and Rabin-Karp.

# Brute Force

- The Brute Force algorithm compares the pattern to the text, one character at a time, until unmatching characters are found:

```
TWO ROADS DIVERGED IN A YELLOW WOOD
ROADS
```
```
TWO ROADS DIVERGED IN A YELLOW WOOD
 ROADS
```
```
TWO ROADS DIVERGED IN A YELLOW WOOD
  ROADS
```
```
TWO ROADS DIVERGED IN A YELLOW WOOD
   ROADS
```
```
TWO ROADS DIVERGED IN A YELLOW WOOD
    ROADS
```

  - Compared characters are italicized.
  - Correct matches are in boldface type.

- The algorithm can be designed to stop on either the first occurrence of the pattern, or upon reaching the end of the text.

# Brute Force Pseudo-Code

- Here's the pseudo-code

```
do
  if (text letter == pattern letter)
    compare next letter of pattern to next
    letter of text
  else
    move pattern down text by one letter
while (entire pattern found or end of text)
```

```
tetththeheehthtehtheththehehtht
the
tetththeheehthtehtheththehehtht
 the
tetththeheehthtehtheththehehtht
  the
tetththeheehthtehtheththehehtht
   the
tetththeheehthtehtheththehehtht
    the
tetththeheehthtehtheththehehtht
     the
```

# Brute Force-Complexity

- Given a pattern M characters in length, and a text N characters in length...
- **Worst case**: compares pattern to each substring of text of length M. For example, M=5.

1) *AAAAA*AAAAAAAAAAAAAAAAAAAAAAAH
   *AAAAH* **5 comparisons made**
2) *AAAAA*AAAAAAAAAAAAAAAAAAAAAAAH
   *AAAAH* **5 comparisons made**
3) *AAAAA*AAAAAAAAAAAAAAAAAAAAAAAH
   *AAAAH* **5 comparisons made**
4) *AAAAA*AAAAAAAAAAAAAAAAAAAAAAAH
   *AAAAH* **5 comparisons made**
5) *AAAAA*AAAAAAAAAAAAAAAAAAAAAAAH
   *AAAAH* **5 comparisons made**

....

N) AAAAAAAAAAAAAAAAAAAAAAAAA*AAAAH*
   **5 comparisons made** *AAAAH*

- Total number of comparisons: M (N-M+1)
- Worst case time complexity: O(MN)

# Brute Force-Complexity(cont.)

- Given a pattern M characters in length, and a text N characters in length...
- **Best case if pattern found**: Finds pattern in first M positions of text. For example, M=5.

1) *AAAAA*AAAAAAAAAAAAAAAAAAAAAAAH
*AAAAA* **5 comparisons made**

- Total number of comparisons: M
- Best case time complexity: O(M)

# Brute Force-Complexity(cont.)

- Given a pattern M characters in length, and a text N characters in length...
- **Best case if pattern not found**: Always mismatch on first character. For example, M=5.

1) *A*AAAAAAAAAAAAAAAAAAAAAAAAAAAH
   *O*OOOH **1 comparison made**
2) A*A*AAAAAAAAAAAAAAAAAAAAAAAAAAH
   *O*OOOH **1 comparison made**
3) AA*A*AAAAAAAAAAAAAAAAAAAAAAAAAH
   *O*OOOH **1 comparison made**
4) AAA*A*AAAAAAAAAAAAAAAAAAAAAAAAH
   *O*OOOH **1 comparison made**
5) AAAA*A*AAAAAAAAAAAAAAAAAAAAAAAH
   *O*OOOH **1 comparison made**

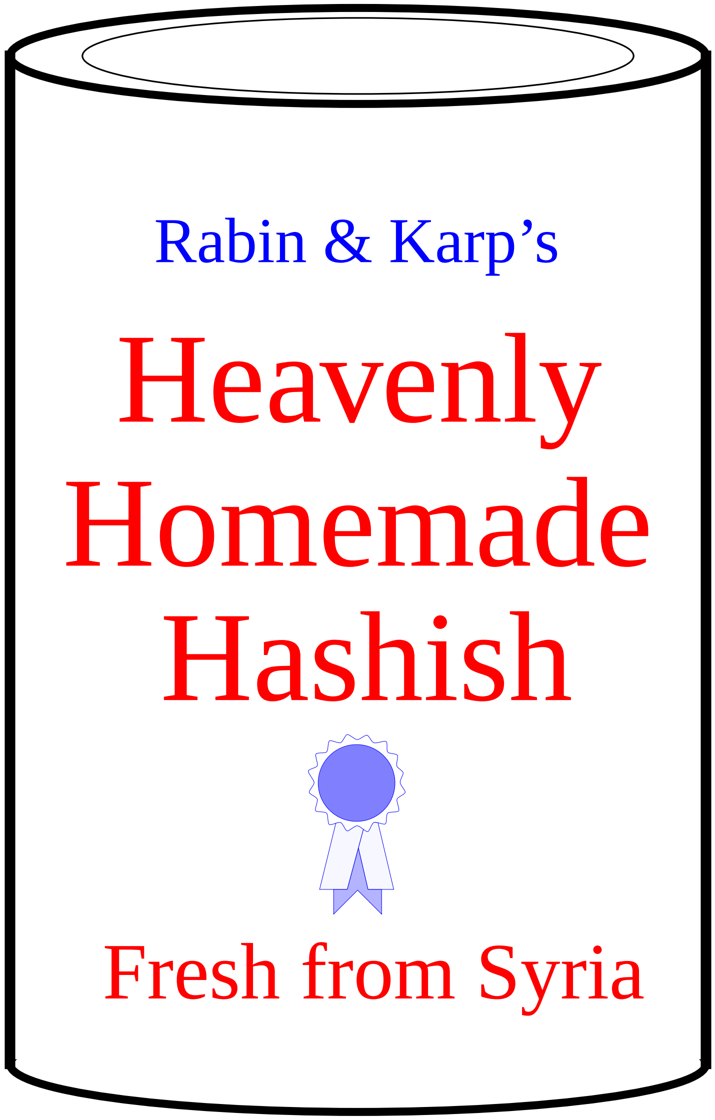
...

N) AAAAAAAAAAAAAAAAAAAAAAAAA*A*AAAH
   **1 comparison made** *O*OOOH

- Total number of comparisons: N
- Best case time complexity: O(N)

# Rabin-Karp

- The Rabin-Karp string searching algorithm uses a hash function to speed up the search.



# Rabin-Karp

- The Rabin-Karp string searching algorithm calculates a **hash value** for the pattern, and for each M-character subsequence of text to be compared.
- If the hash values are unequal, the algorithm will calculate the hash value for next M-character sequence.
- If the hash values are equal, the algorithm will do a Brute Force comparison between the pattern and the M-character sequence.
- In this way, there is only one comparison per text subsequence, and Brute Force is only needed when hash values match.
- Perhaps a figure will clarify some things...

# Rabin-Karp Example

Hash value of “AAAAA” is 37

Hash value of “AAAAH” is 100

1) AAAAAAAAAAAAAAAAAAAAAAAAAAAH
AAAAH
37≠100 **1 comparison made**

2) AAAAAAAAAAAAAAAAAAAAAAAAAAAH
AAAAH
37≠100 **1 comparison made**

3) AAAAAAAAAAAAAAAAAAAAAAAAAAAH
AAAAH
37≠100 **1 comparison made**

4) AAAAAAAAAAAAAAAAAAAAAAAAAAAH
AAAAH
37≠100 **1 comparison made**

...

N) AAAAAAAAAAAAAAAAAAAAAAAAAAAH
AAAAH
**6 comparisons made** 100=100

# Rabin-Karp Pseudo-Code

*pattern is M characters long*

hash_p=hash value of pattern
hash_t=hash value of first M letters in
body of text

```
do
  if (hash_p == hash_t)
    brute force comparison of pattern
    and selected section of text
  hash_t = hash value of next section of
           text, one character over
while (end of text or
       brute force comparison == true)
```

# Rabin-Karp

- Common Rabin-Karp questions:

  "What is the hash function used to calculate values for character sequences?"

  "Isn't it time consuming to hash every one of the M-character sequences in the text body?"

  "Is this going to be on the final?"

- To answer some of these questions, we'll have to get mathematical.

# Rabin-Karp Math

- Consider an M-character sequence as an M-digit number in base $\boldsymbol{b}$, where $\boldsymbol{b}$ is the number of letters in the alphabet. The text subsequence t[i .. i+M-1] is mapped to the number

$$\boldsymbol{x}(i) = \boldsymbol{t}[i]\cdot\boldsymbol{b}^{M-1} + \boldsymbol{t}[i+1]\cdot\boldsymbol{b}^{M-2} + \ldots + \boldsymbol{t}[i+M-1]$$

- Furthermore, given x(i) we can compute x(i+1) for the next subsequence t[i+1 .. i+M] in constant time, as follows:

$$\boldsymbol{x}(i+1) = \boldsymbol{t}[i+1]\cdot\boldsymbol{b}^{M-1} + \boldsymbol{t}[i+2]\cdot\boldsymbol{b}^{M-2} + \ldots + \boldsymbol{t}[i+M]$$

$\boldsymbol{x}(i+1) = \boldsymbol{x}(i)\cdot\boldsymbol{b}$ Shift left one digit

$- \boldsymbol{t}[i]\cdot\boldsymbol{b}^{M}$ Subtract leftmost digit

$+ \boldsymbol{t}[i+M]$ Add new rightmost digit

- In this way, we never explicitly compute a new value. We simply adjust the existing value as we move over one character.

# Rabin-Karp Mods

- If M is large, then the resulting value (~bM) will be enormous. For this reason, we hash the value by taking it **mod** a prime number ***q***.
- The **mod** function (% in Java) is particularly useful in this case due to several of its inherent properties:
  - $[(x \bmod q) + (y \bmod q)] \bmod q = (x+y) \bmod q$
  - $(x \bmod q) \bmod q = x \bmod q$
- For these reasons:

$$\boldsymbol{h}(i) = ((\boldsymbol{t}[i]\cdot \boldsymbol{b}^{M-1} \bmod \boldsymbol{q}) + (\boldsymbol{t}[i+1]\cdot \boldsymbol{b}^{M-2} \bmod \boldsymbol{q}) + \ldots + (\boldsymbol{t}[i+M-1] \bmod \boldsymbol{q})) \bmod \boldsymbol{q}$$

$\boldsymbol{h}(i+1) = ( \boldsymbol{h}(i)\cdot \boldsymbol{b} \bmod \boldsymbol{q}$

Shift left one digit

$-\boldsymbol{t}[i]\cdot \boldsymbol{b}^{M} \bmod \boldsymbol{q}$

Subtract leftmost digit

$+\boldsymbol{t}[i+M] \bmod \boldsymbol{q}\ )$

Add new rightmost digit

$\bmod \boldsymbol{q}$

# Rabin-Karp Pseudo-Code

*pattern is M characters long*

hash_p=hash value of pattern

hash_t =hash value of first M letters in
body of text

```
do
  if (hash_p == hash_t)
    brute force comparison of pattern
    and selected section of text
  hash_t = hash value of next section of
            text, one character over
while (end of text or
        brute force comparison == true)
```

# Rabin-Karp Complexity

- If a sufficiently large prime number is used for the *hash function*, the hashed values of two different patterns will usually be distinct.
- If this is the case, searching takes O(N) time, where N is the number of characters in the larger body of text.
- It is always possible to construct a scenario with a worst case complexity of O(MN). This, however, is likely to happen only if the prime number used for hashing is small.

# The Knuth-Morris-Pratt Algorithm

- The Knuth-Morris-Pratt (KMP) string searching algorithm differs from the brute-force algorithm by keeping track of information gained from previous comparisons.
- A failure function (*f*) is computed that indicates how much of the last comparison can be reused if it fais.
- Specifically, *f* is defined to be the longest prefix of the pattern P[0,..,j] that is also a suffix of P[1,..,j]
  - Note: **not** a suffix of P[0,..,j]
- Example:
  - value of the KMP failure function:

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

- This shows how much of the beginning of the string matches up to the portion immediately preceding a failed comparison.
  - if the comparison fails at (4), we know the a,b in positions 2,3 is identical to positions 0,1

# The KMP Algorithm (contd.)

- Time Complexity Analysis
- define $k = i - j$
- In every iteration through the while loop, one of three things happens.
  - 1) if $T[i] = P[j]$, then $i$ increases by 1, as does $j$ $k$ remains the same.
  - 2) if $T[i]$ != $P[j]$ and $j > 0$, then $i$ does not change and $k$ increases by at least 1, since $k$ changes from $i - j$ to $i - f(j-1)$
  - 3) if $T[i]$ != $P[j]$ and $j = 0$, then $i$ increases by 1 and $k$ increases by 1 since $j$ remains the same.
- Thus, each time through the loop, either $i$ or $k$ increases by at least 1, so the greatest possible number of loops is $2n$
- This of course assumes that $f$ has already been computed.
- However, $f$ is computed in much the same manner as KMPMatch so the time complexity argument is analogous. KMPFailureFunction is $\boldsymbol{O}(m)$
- Total Time Complexity: $\boldsymbol{O}(n + m)$

# The KMP Algorithm (contd.)

- the KMP string matching algorithm: Pseudo-Code

Algorithm KMPMatch(*T*,*P*)
  Input: Strings *T* (text) with *n* characters and *P* (pattern) with *m* characters.
  Output: Starting index of the first substring of *T* matching *P*, or an indication that *P* is not a substring of *T*.

```
f ← KMPFailureFunction(P) {build failure function}
i ← 0
j ← 0
while i < n do
   if P[j] = T[i] then
      if j = m - 1 then
         return i - m - 1 {a match}
      i ← i + 1
      j ← j + 1
   else if j > 0 then {no match, but we have advanced}
      j ← f(j-1) {j indexes just after matching prefix in P}
   else
      i ← i + 1
return "There is no substring of T matching P"
```

# The KMP Algorithm (contd.)

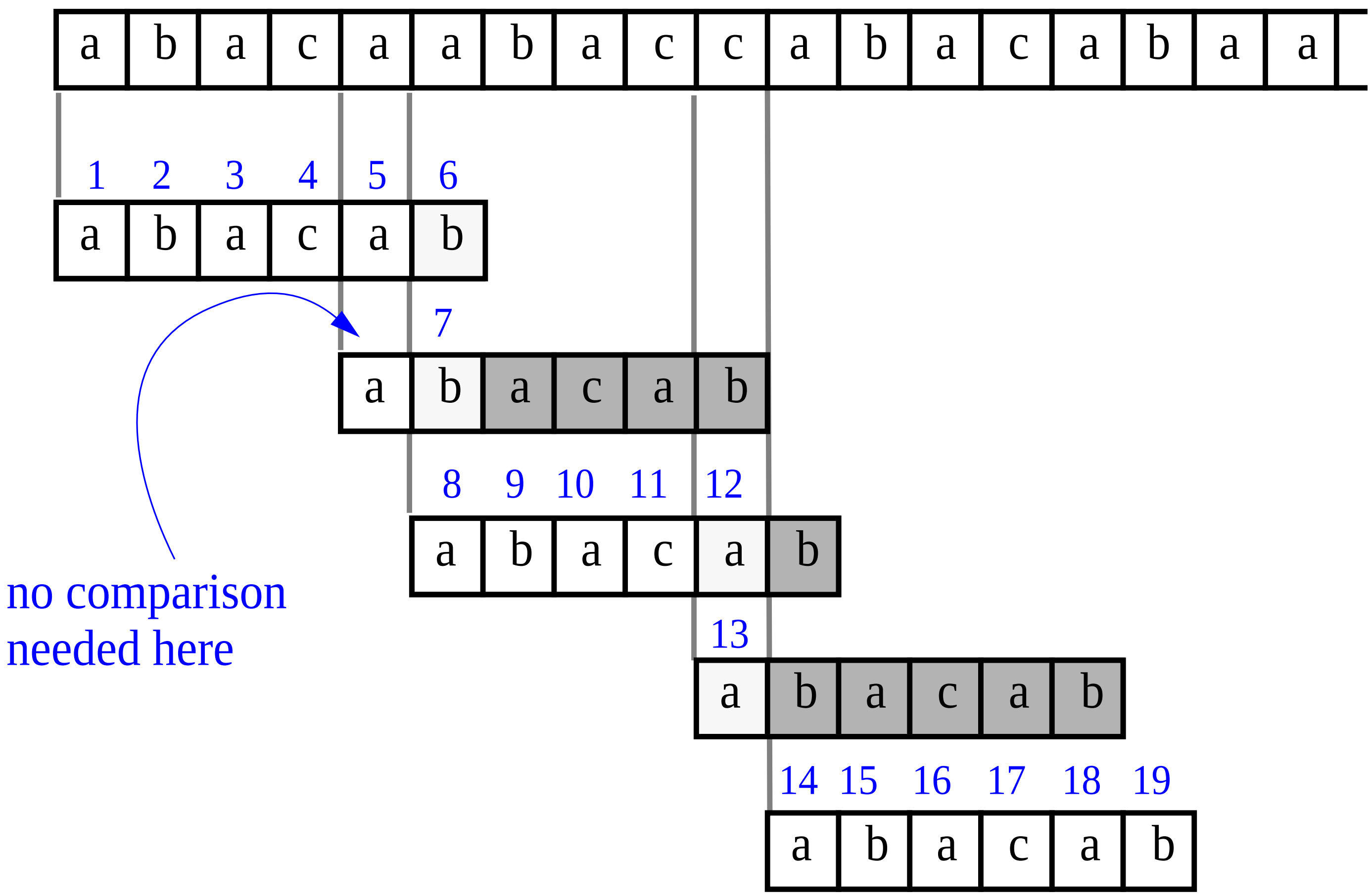
- The KMP failure function: Pseudo-Code

Algorithm KMPFailureFunction($P$);
Input: String $P$ (pattern) with $m$ characters
Ouput: The faliure function $f$ for $P$, which maps $j$ to the length of the longest prefix of $P$ that is a suffix of $P[1,..,j]$

```
i ← 1
j ← 0
while i ≤ m-1 do
   if P[j] = T[j] then
      {we have matched j + 1 characters}
      f(i) ← j + 1
      i ← i + 1
      j ← j + 1
   else if j > 0 then
      {j indexes just after a prefix of P that matches}
      j ← f(j-1)
   else
      {there is no match}
      f(i) ← 0
      i ← i + 1
```

# The KMP Algorithm (contd.)

- A graphical representation of the KMP string searching algorithm

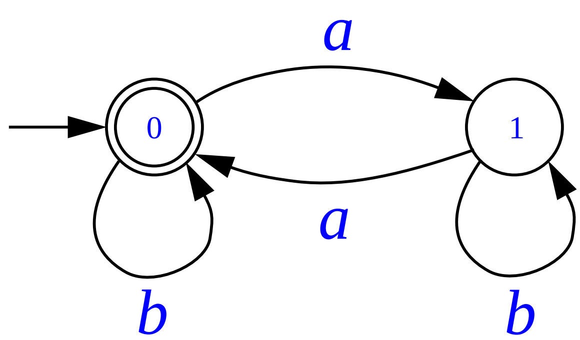


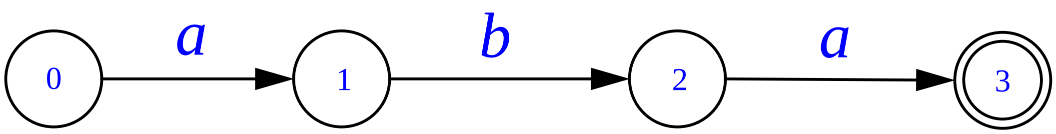
# Regular Expressions

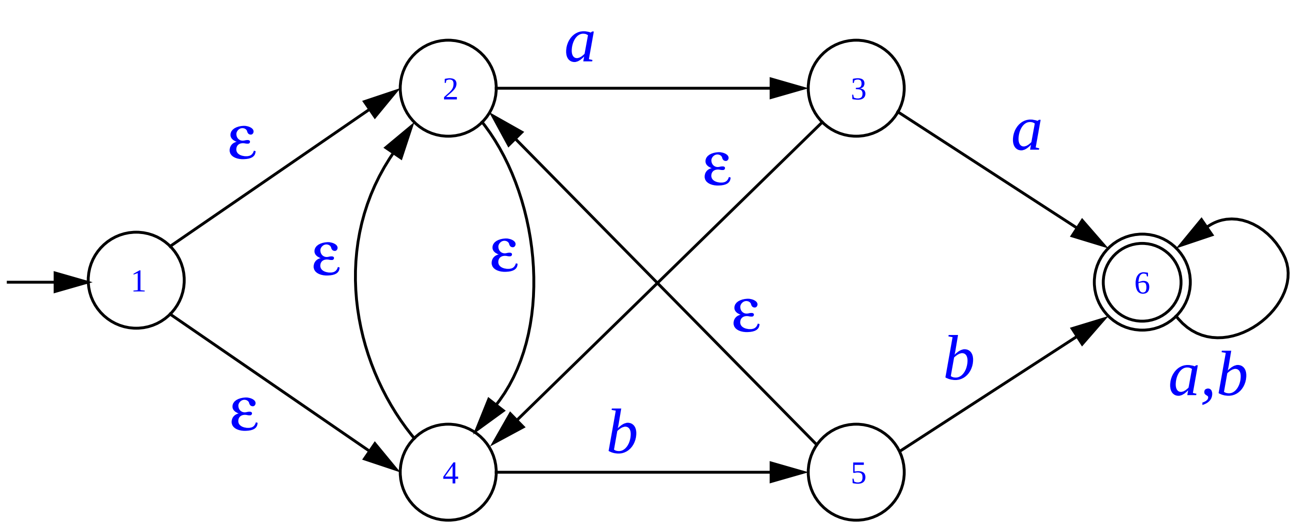
- notation for describing a set of strings, possibly of infinite size
- ε denotes the empty string
- **ab + c** denotes the set {ab, c}
- **a*** denotes the set {ε, a, aa, aaa, ...}
- Examples
  - **(a+b)*** all the strings from the alphabet {a,b}
  - **b*(ab*a)*b*** strings with an even number of a's
  - **(a+b)*sun(a+b)*** strings containing the pattern "sun"
  - **(a+b)(a+b)(a+b)a** 4-letter strings ending in a

# Finite State Automaton

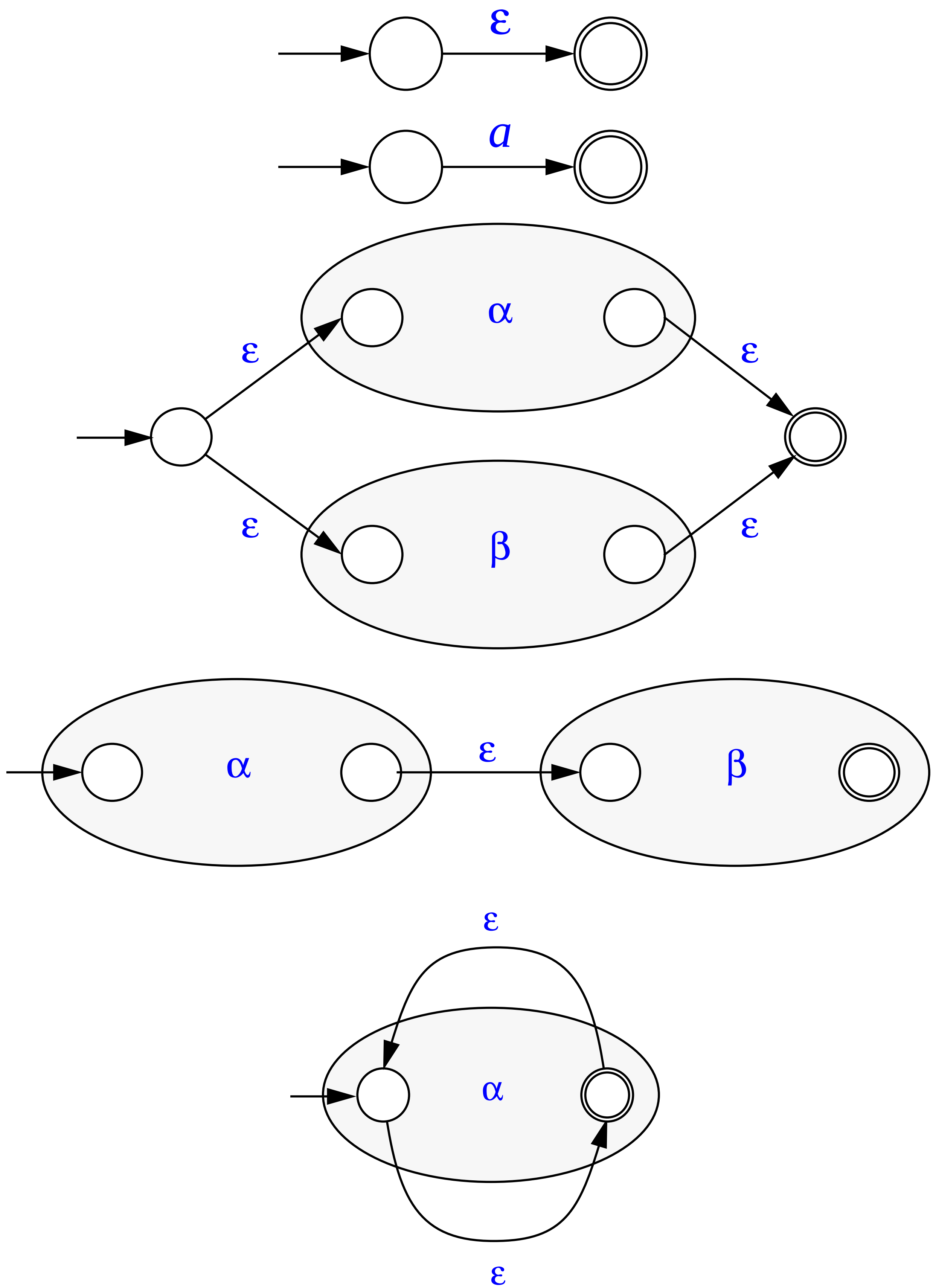
- “machine” for processing strings



# Composition of FSA's



# Tries

- A trie is a tree-based date structure for storing strings in order to make pattern matching faster.
- Tries can be used to perform **prefix queries** for information retrieval. Prefix queries search for the longest prefix of a given string X that matches a prefix of some string in the trie.
- A trie supports the following operations on a set S of strings:

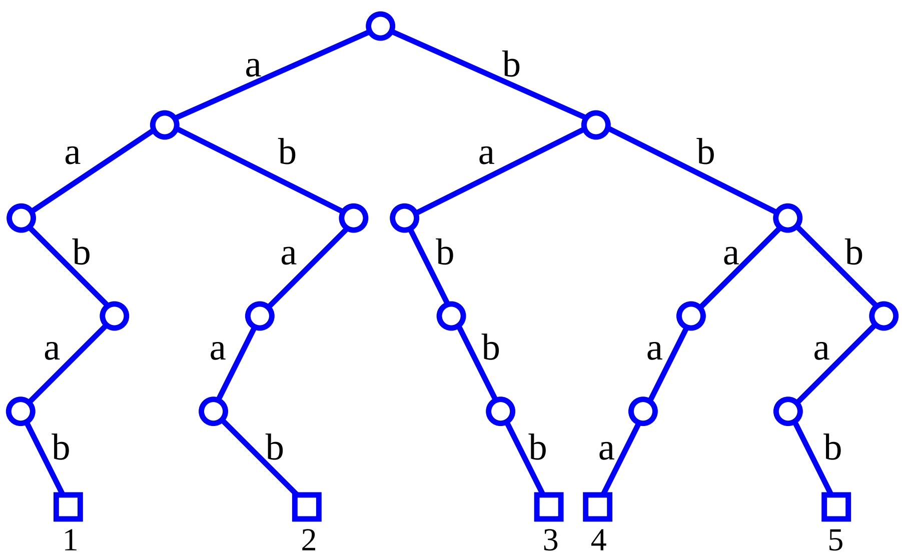
  insert(X): Insert the string X into S
  **Input**: String **Ouput**: None

  remove(X): Remove string X from S
  **Input**: String **Output**: None

  prefixes(X): Return all the strings in S that have a longest prefix of X
  **Input**: String **Output**: Enumeration of strings

# Tries (cont.)

- Let *S* be a set of strings from the alphabet Σ such that no string in *S* is a prefix to another string. A standard trie for *S* is an ordered tree *T* that:
  - Each edge of *T* is labeled with a character from Σ
  - The ordering of edges out of an internal node is determined by the alphabet Σ
  - The path from the root of *T* to any node represents a prefix in Σ that is equal to the concantenation of the characters encountered while traversing the path.
- For example, the standard trie over the alphabet Σ = {a, b} for the set {aabab, abaab, babbb, bbaaa, bbab}



# Tries (cont.)

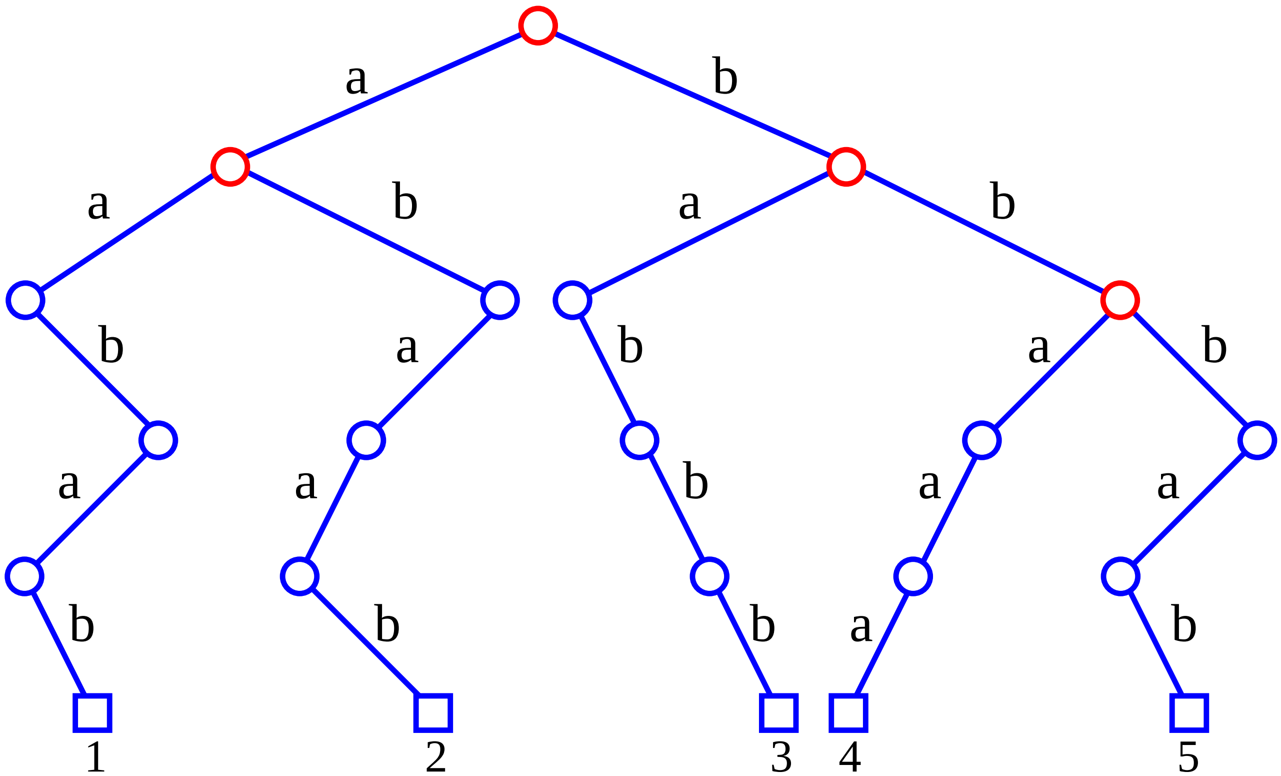
- An internal node can have 1 to *d* children when d is the size of the alphabet. Our example is essentially a binary tree.
- A path from the root of *T* to an internal node *v* at depth *i* corresponds to an *i*-character prefix of a string of *S*.
- We can implement a trie with an ordered tree by storing the character associated with an edge at the child node below it.

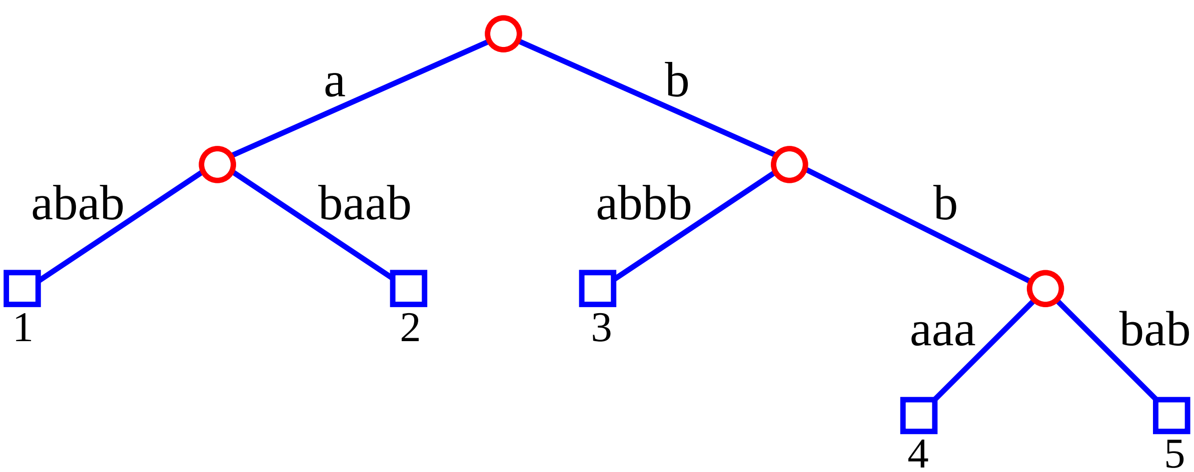
# Compressed Tries

- A compressed trie is like a standard trie but makes sure that each trie had a degree of at least 2. Single child nodes are compressed into an single edge.
- A **critical node** is a node v such that v is labeled with a string from S, v has at least 2 children, or v is the root.
- To convert a standard trie to a compressed trie we replace an edge $(v_0, v_1)$ each chain on nodes $(v_0, v_1 \ldots v_k)$ for k 2 such that
  - $v_0$ and $v_1$ are critical but $v_1$ is critical for $0<i<k$
  - each $v_1$ has only one child
- Each internal node in a compressed tire has at least two children and each external is associated with a string. The compression reduces the total space for the trie from O(*m*) where *m* is the sum of the the lengths of strings in *S* to O(*n*) where *n* is the number of strings in *S*.

# Compressed Tries (cont.)

- An example:



# Prefix Queries on a Trie

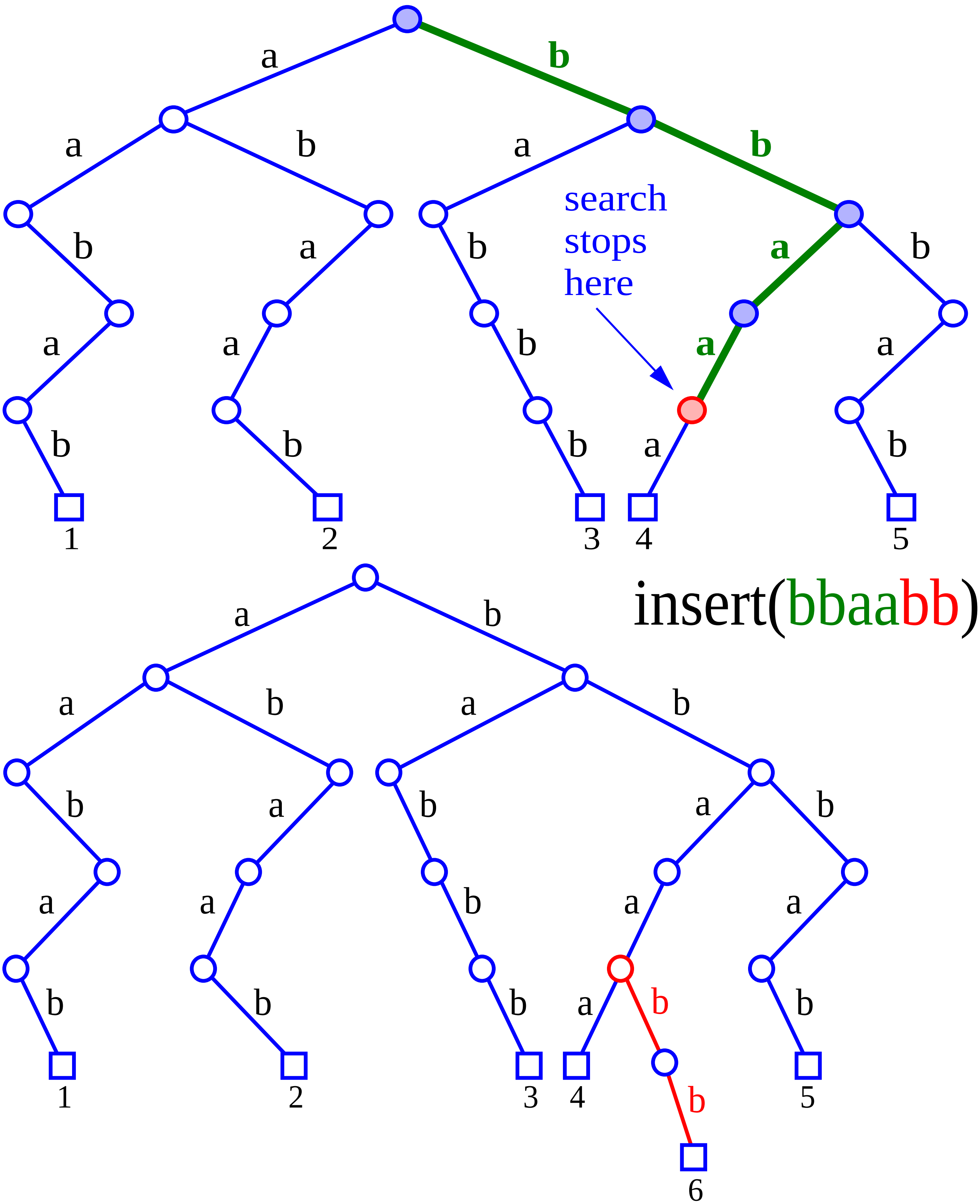
**Algorithm** prefixQuery(*T*, *X*):
  **Input**: Trie *T* for a set S of strings and a query string *X*
  **Output**: The node *v* of *T* such that the labeled nodes of
          the subtree of *T* rooted at *v* store the strings
          of S with a longest prefix in common with *X*
  *v*←*T*.root()
  *i*←0    {*i* is an index into the string *X*}
  **repeat**
    **for** each child *w* of *v* **do**
    let *e* be the edge (*v*,*w*)
    *Y*←string(*e*) {*Y* is the substring associated with *e*}
    *l*←*Y*.length() {*l*=1 if *T* is a standard trie}
    Z¨*X*.substring(*i*, *i*+*l*-1) {Z holds the next *l* charac
        ters of *X*}
    **if** Z = Y **then**
      *v*←w
      *i*←*i*+1{move to W, incrementing *i* past Z}
      **break** out of the **for** loop
    **else if** a proper prefix of Z matched a proper prefix
      of Y **then**
      *v*←w
      **break** out ot the **repeat** loop
**until** *v* is external **or** *v*≠w
**return** *v*

# Insertion and Deletion

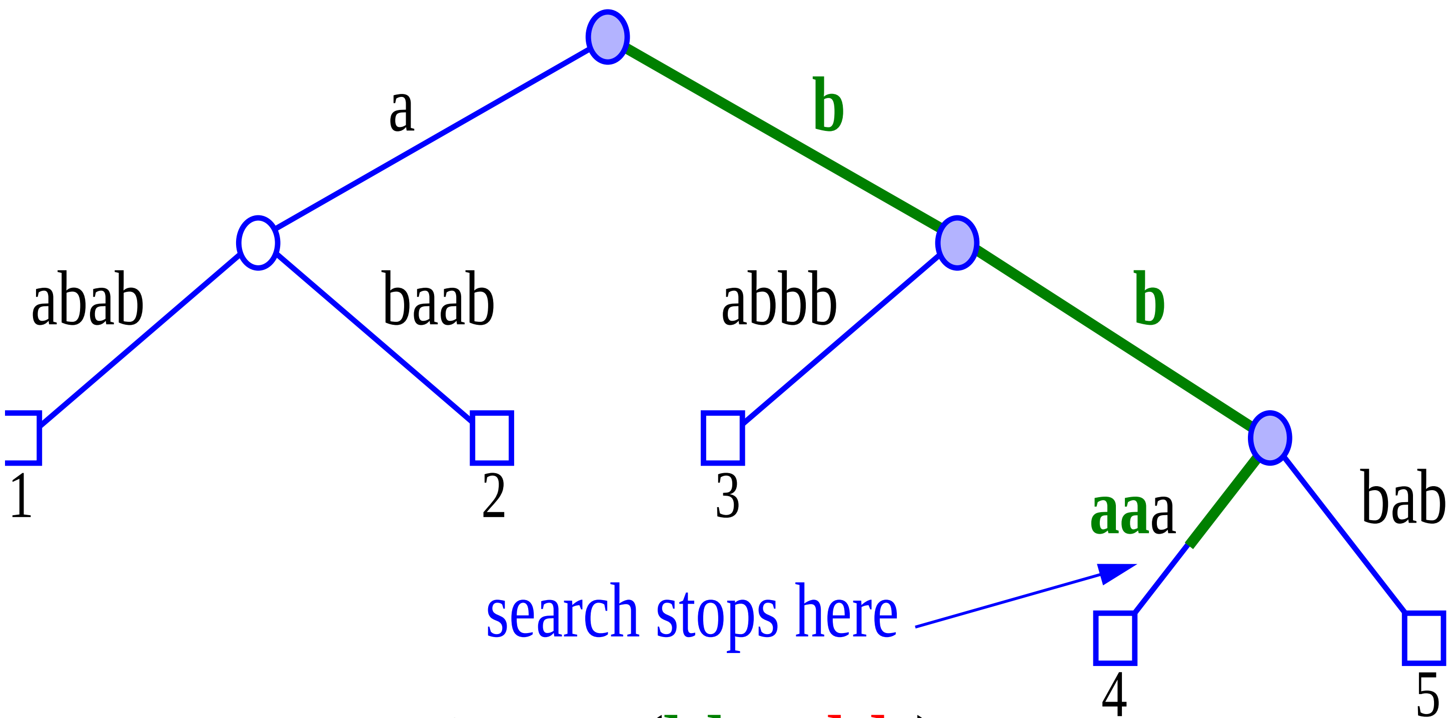
- Insertion: We first perform a prefix query for string X. Let us examine the ways a prefix query may end in terms of insertion.
  - The query terminates at node v. Let $X_1$ be the prefix of X that matched in the trie up to node v and $X_2$ be the rest of X. If $X_2$ is an empt string we label v with X and the end. Otherwise we creat a new external node w and label it with X.
  - The query terminates at an edge e=(v, w) because a prefix of X match prefix(v) and a proper prefix of string Y associated with e. Let $Y_1$ be the part of Y that X mathed to and $Y_2$ the rest of Y. Likewise for $X_1$ and $X_2$. Then $X=X_1+X_2$ = prefix(v) $+Y_1+X_2$. We create a new node u and split the edges(v, u) and (u, w). If X2 is empty then w label u with X. Otherwise we creat a node z which is external and label it X.

- Insertion is O(dn) when d is the size of the alphabet and n is the length of the string t insert.

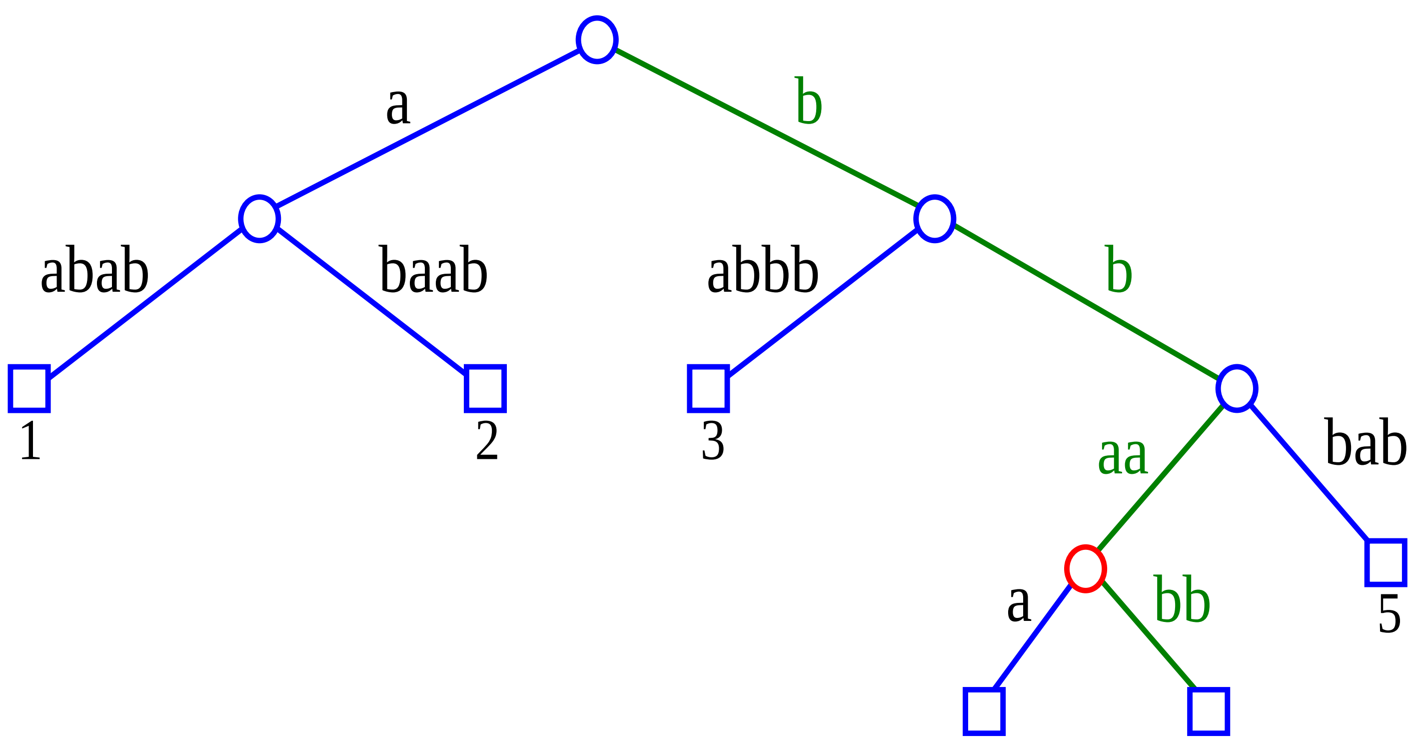
# Insertion and Deletion (cont.)



# Insertion and Deletion (cont.)




insert(bbaabb)



# Lempel Ziv Encoding

- Constructing the trie:
  - Let phrase 0 be the null string.
  - Scan through the text
  - If you come across a letter you haven't seen before, add it to the top level of the trie.
  - If you come across a letter you've already seen, scan down the trie until you can't match any more chracters, add a node to the trie representing the new string.
  - Insert the pair (nodeIndex, lastChar) into the compressed string.
- Reconstructing the string:
  - Every time you see a '0' in the compressed string add the next character in the compressed string directly to the new string.
  - For each non-zero nodeIndex, put the substring corresponding to that node into the new string, followed by the next character in the compressed string.

# Lempel Ziv Encoding (contd.)

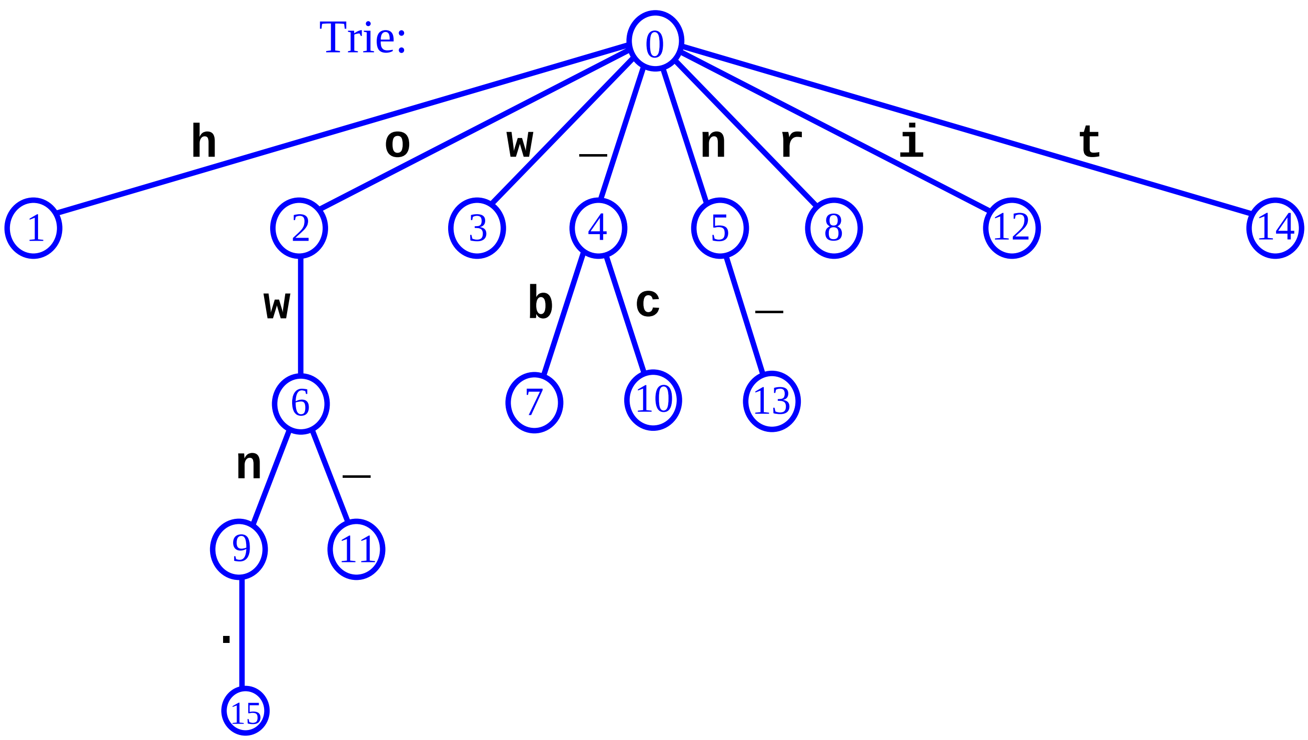
- A graphical example:

Uncompressed text: (nil) `how now brown cow in town.`

phrases: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

Compressed text: 0**h**0**o**0**w**0_0**n**2**w**4**b**0**r**6**n**4**c**6_0**i**5_0**t**9**.**

Trie:

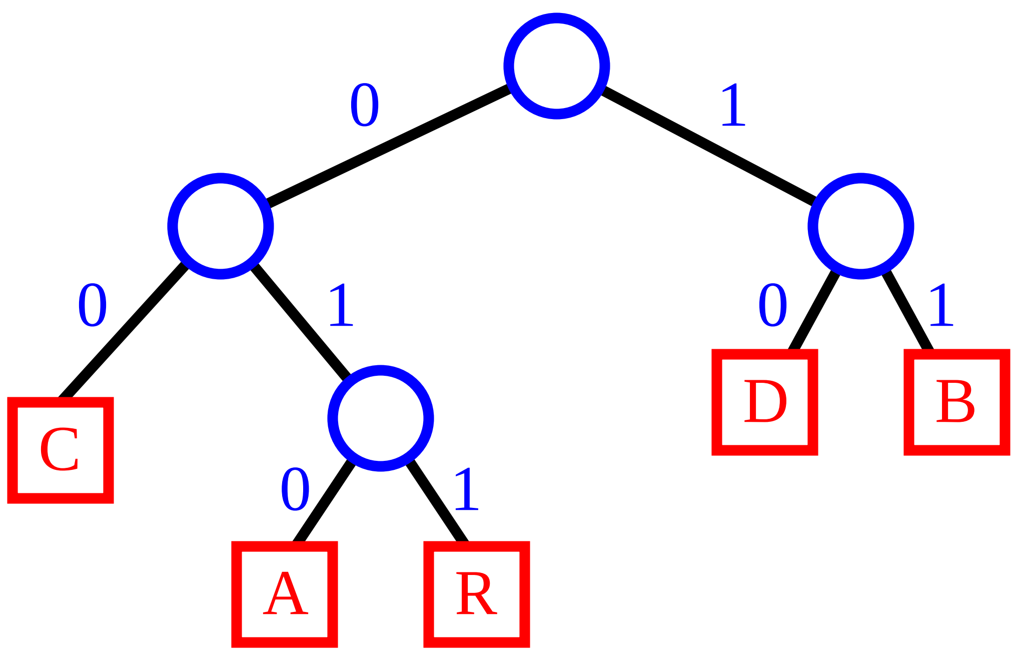


# File Compression

- text files are usually stored by representing each character with an 8-bit ASCII code (type man ascii in a Unix shell to see the ASCII encoding)
- the ASCII encoding is an example of **fixed-length encoding**, where each character is represented with the same number of bits
- in order to reduce the space required to store a text file, we can exploit the fact that some characters are more likely to occur than others
- **variable-length encoding** uses binary codes of different lengths for different characters; thus, we can assign fewer bits to frequently used characters, and more bits to rarely used characters.
- Example:
  - text: java
  - encoding: a = “0”, j = “11”, v = “10”
  - encoded text: 110100 (6 bits)
- How to decode?
  - a = “0”, j = “01”, v = “00”
  - encoded text: 010000 (6 bits)
  - is this java, jvv, jaaaa ...

# Encoding Trie

- to prevent ambiguities in decoding, we require that the encoding satisfies the **prefix rule**, that is, no code is a prefix of another code
  - a = “0”, j = “11”, v = “10” satisfies the prefix rule
  - a = “0”, j = “01”, v= “00” does **not** satisfy the prefix rule (the code of a is a prefix of the codes of j and v)
- we use an **encoding trie** to define an encoding that satisfies the prefix rule
  - the characters stored at the external nodes
  - a left edge means 0
  - a right edge means 1




A = 010

B = 11

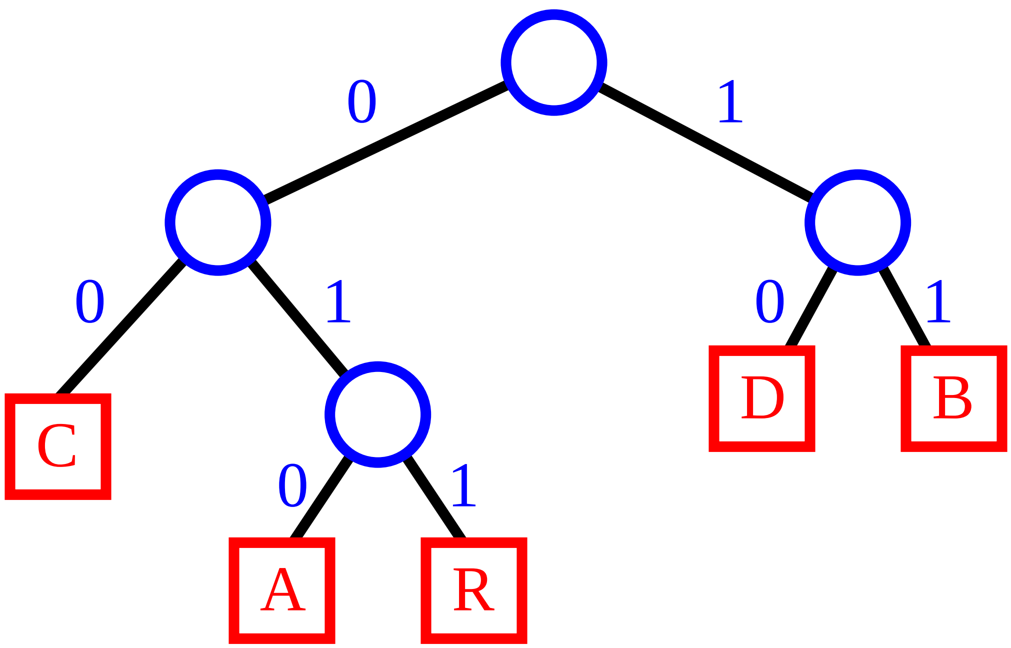
C = 00

D = 10

R = 011

# Example of Decoding

- trie:




A = 010

B = 11

C = 00

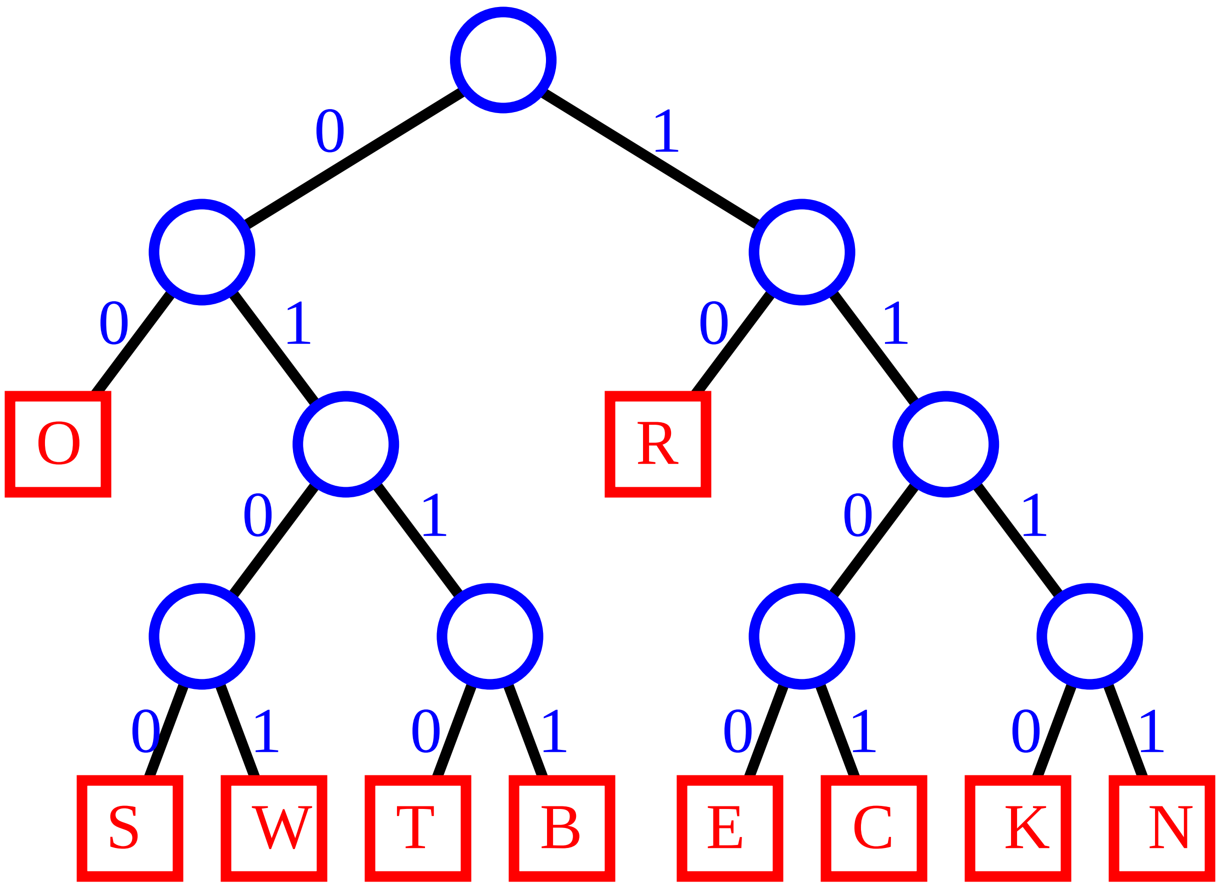
D = 10

R = 011

- encoded text:
  01011011010000101001011011010

- text:

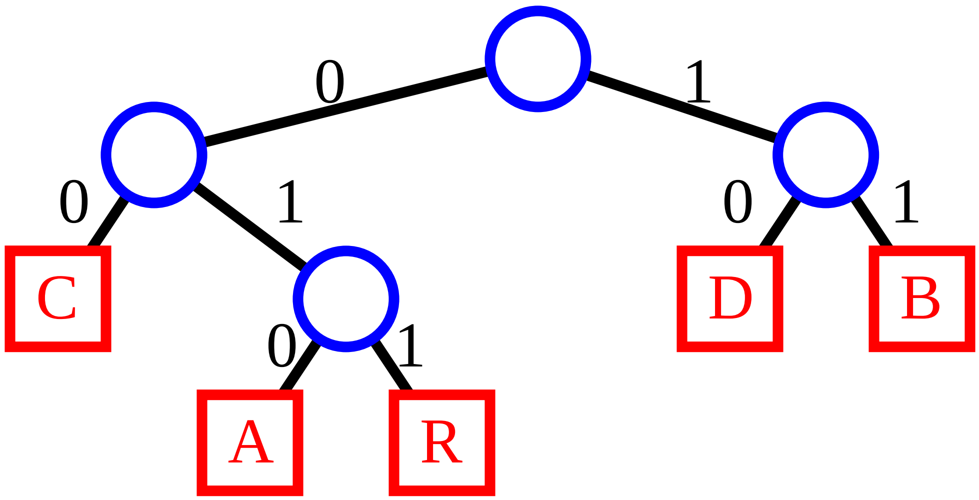
# Trie this!



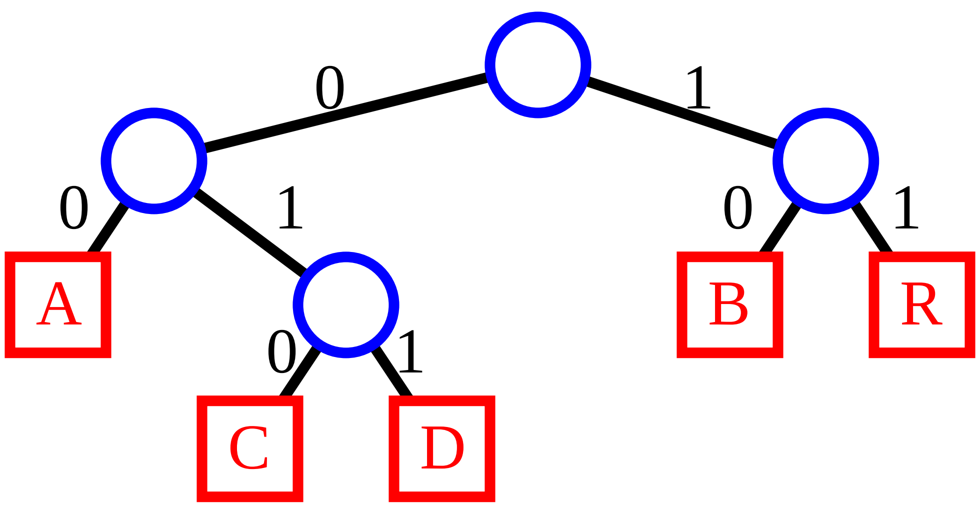

10000111110010011000111011110001010100110101100

# Optimal Compression

- An issue with encoding tries is to insure that the encoded text is as short as possible:

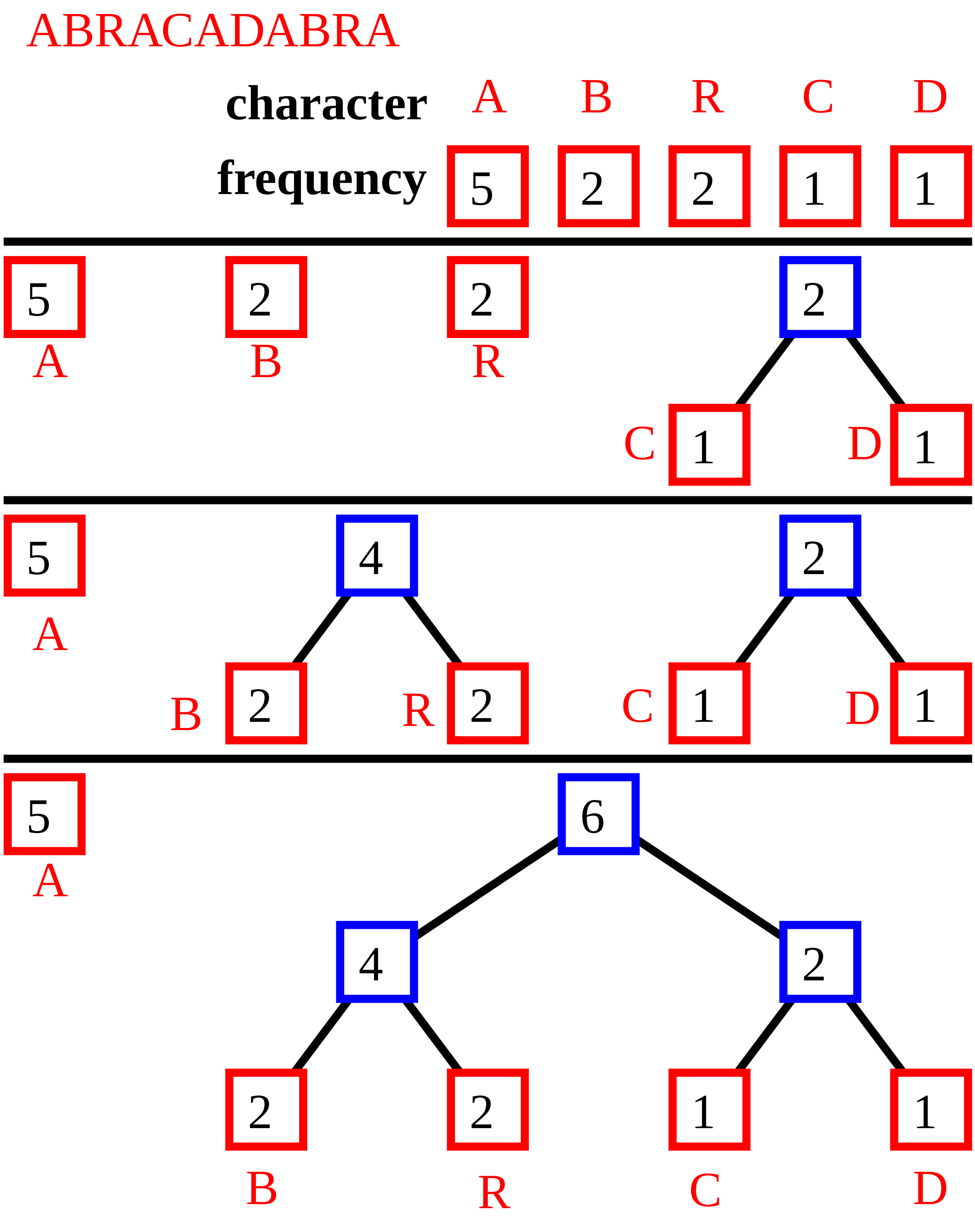



ABRACADABRA
01011011010000101001011011010
**29 bits**

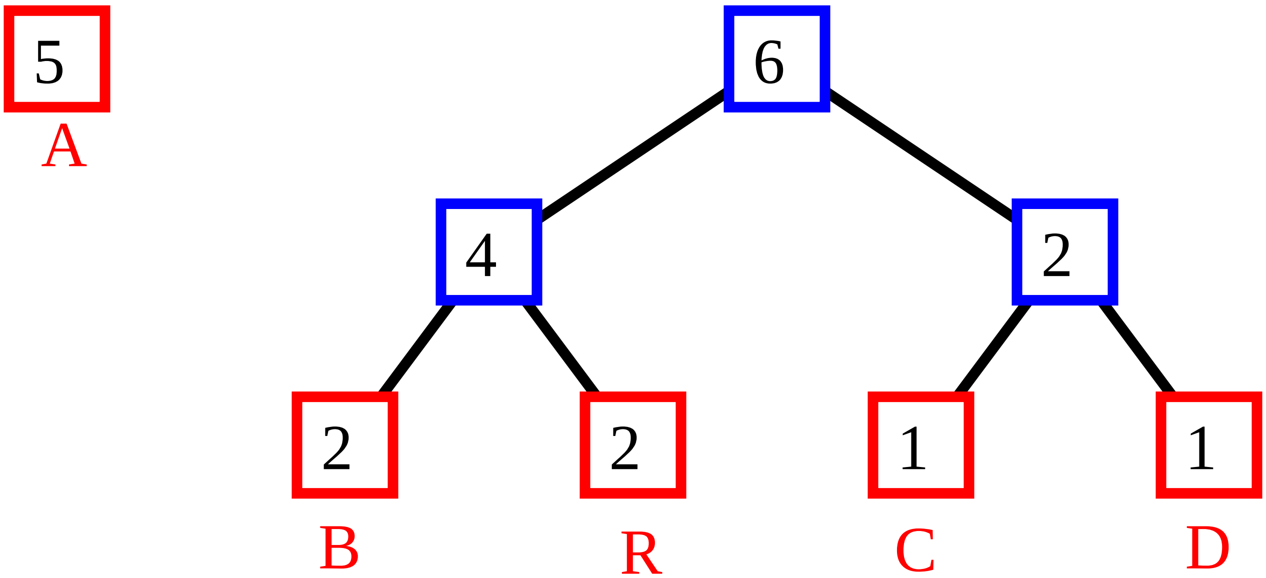


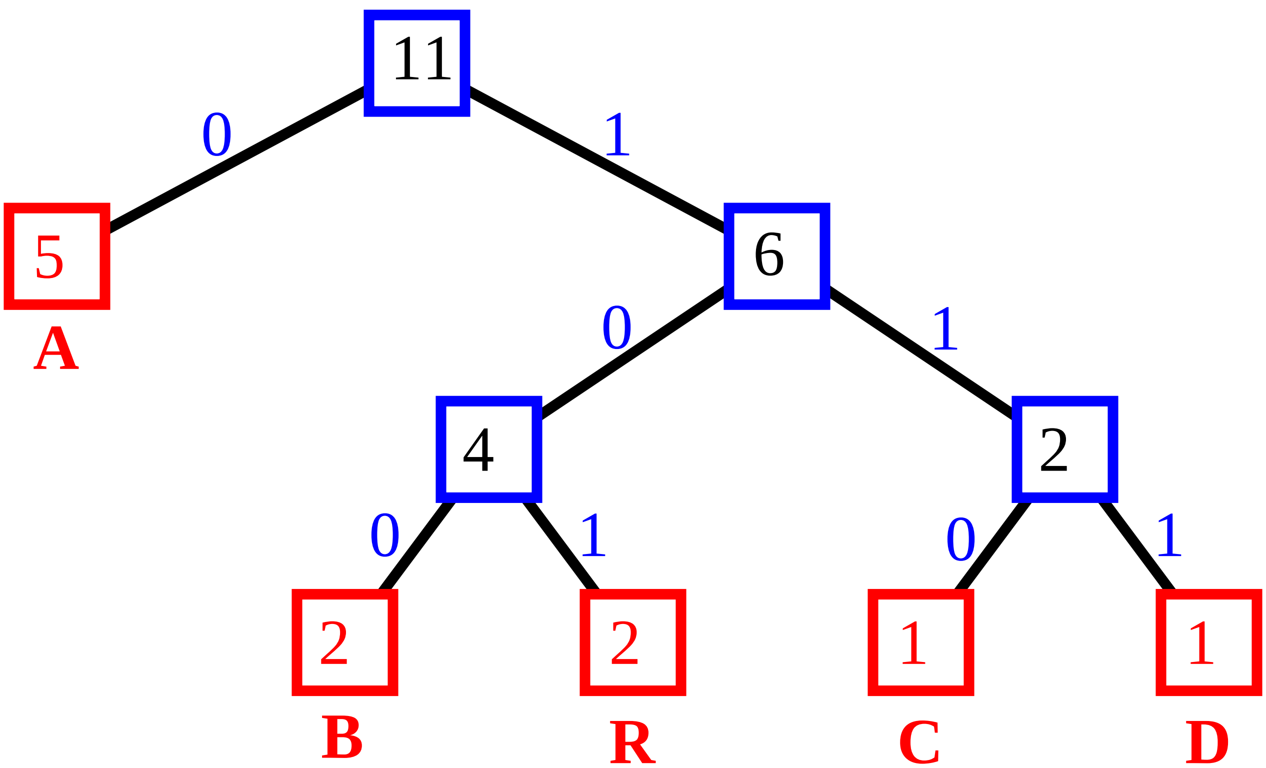

ABRACADABRA
001011000100001100101100
**24 bits**

# Huffman Encoding Trie

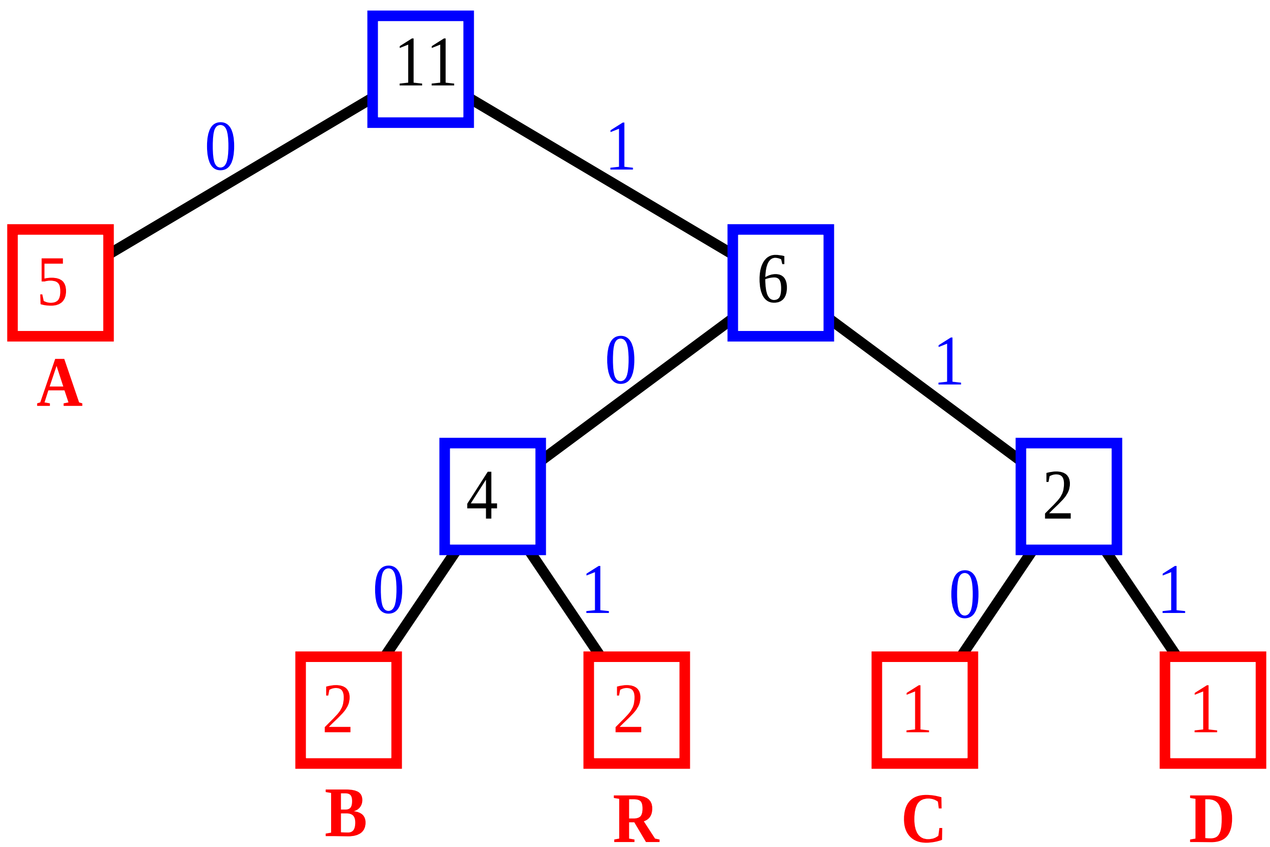


# Huffman Encoding Trie (contd.)



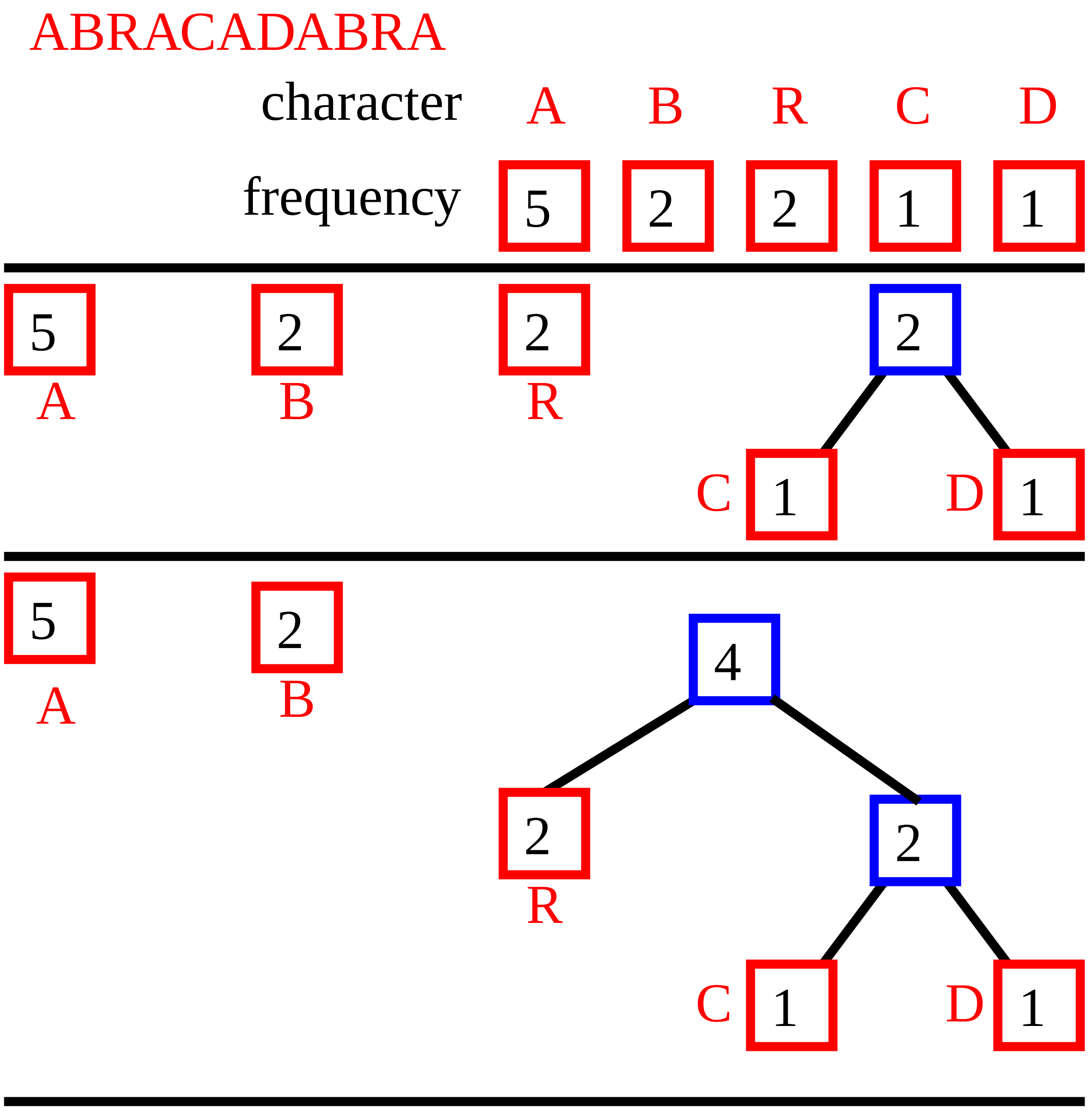
# Final Huffman Encoding Trie



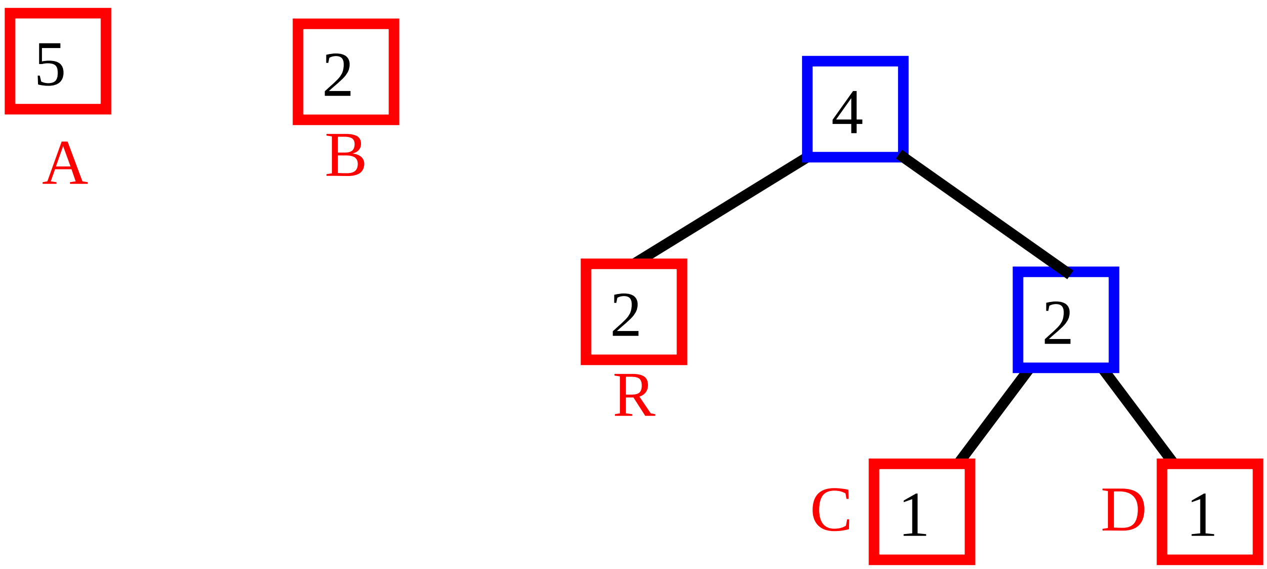

| A | B | R | A | C | A | D | A | B | R | A |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 100 | 101 | 0 | 110 | 0 | 111 | 0 | 100 | 101 | 0 |

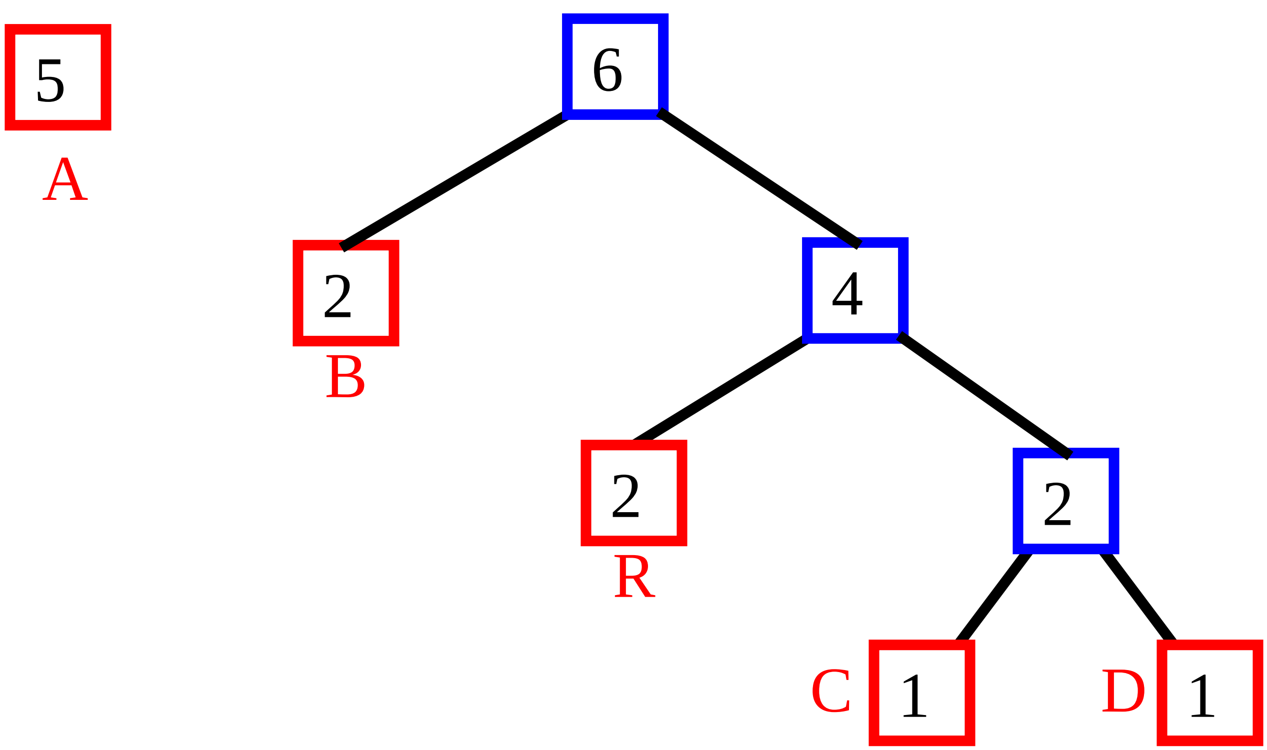
**23 bits**

# Another Huffman Encoding Trie

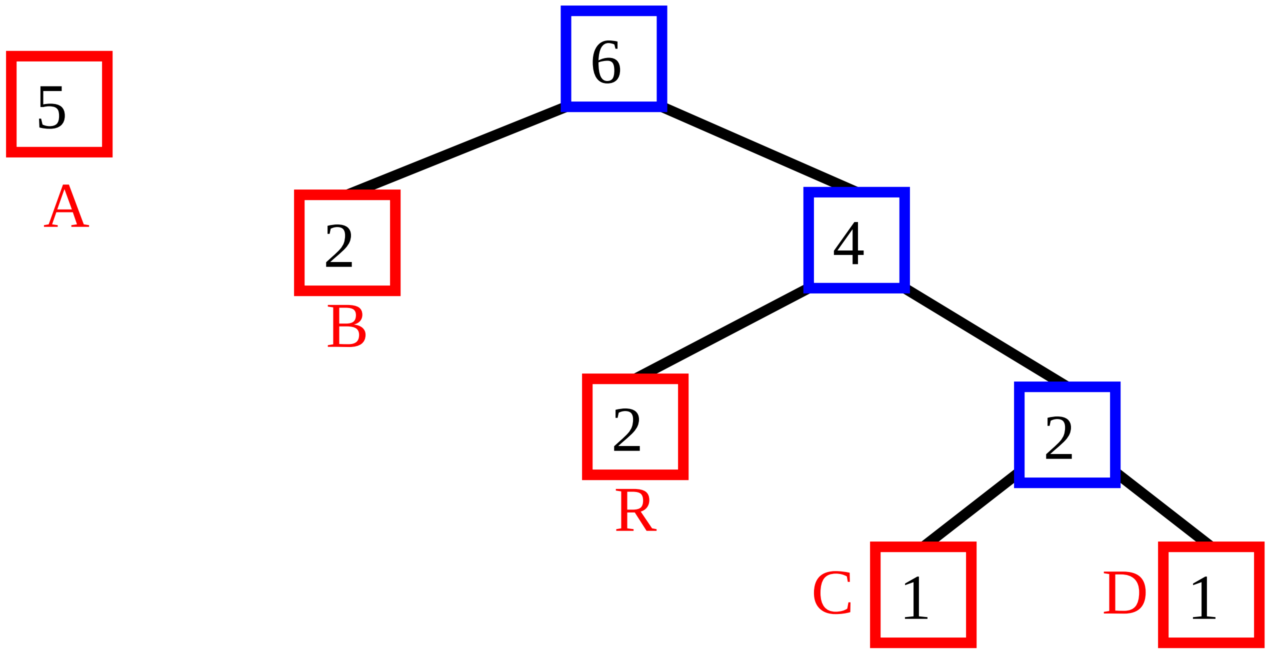


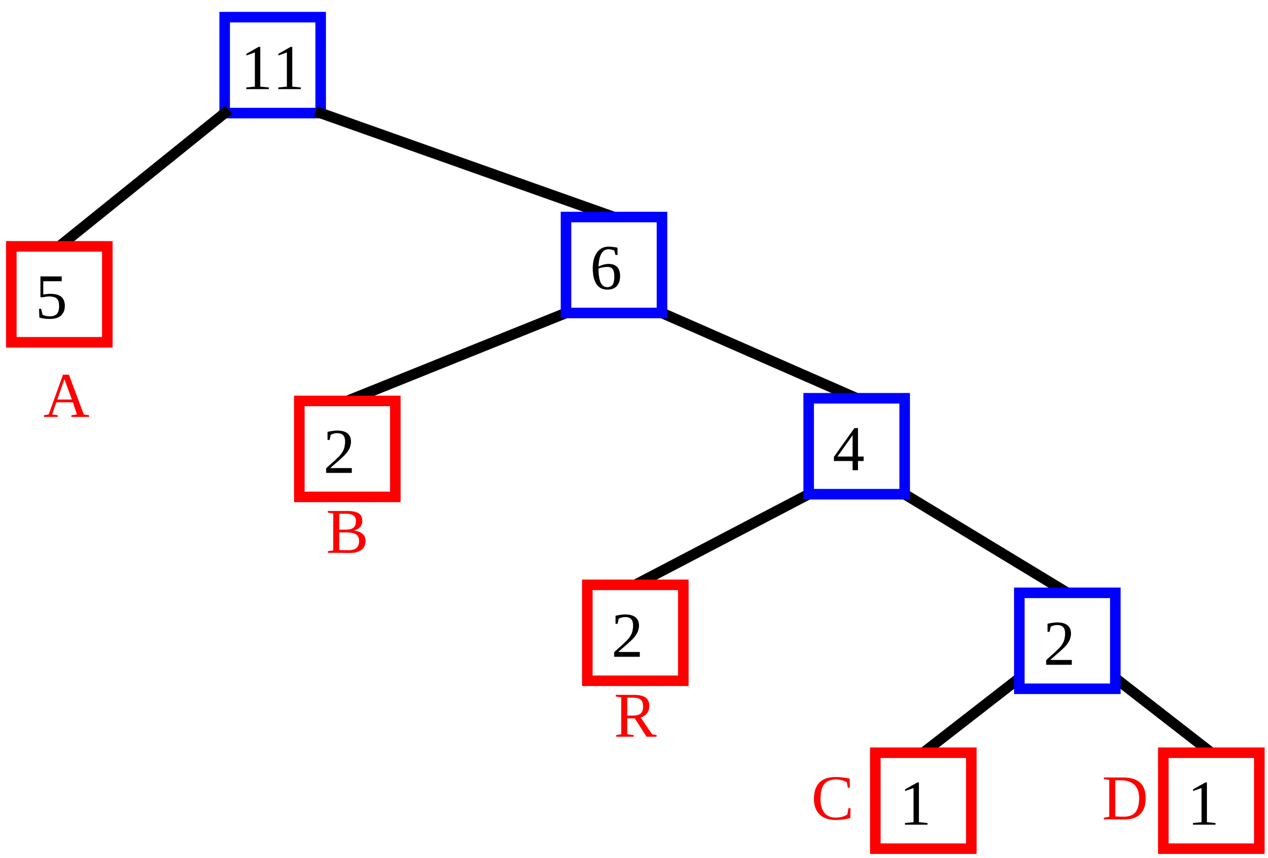
# Another Huffman Encoding Trie



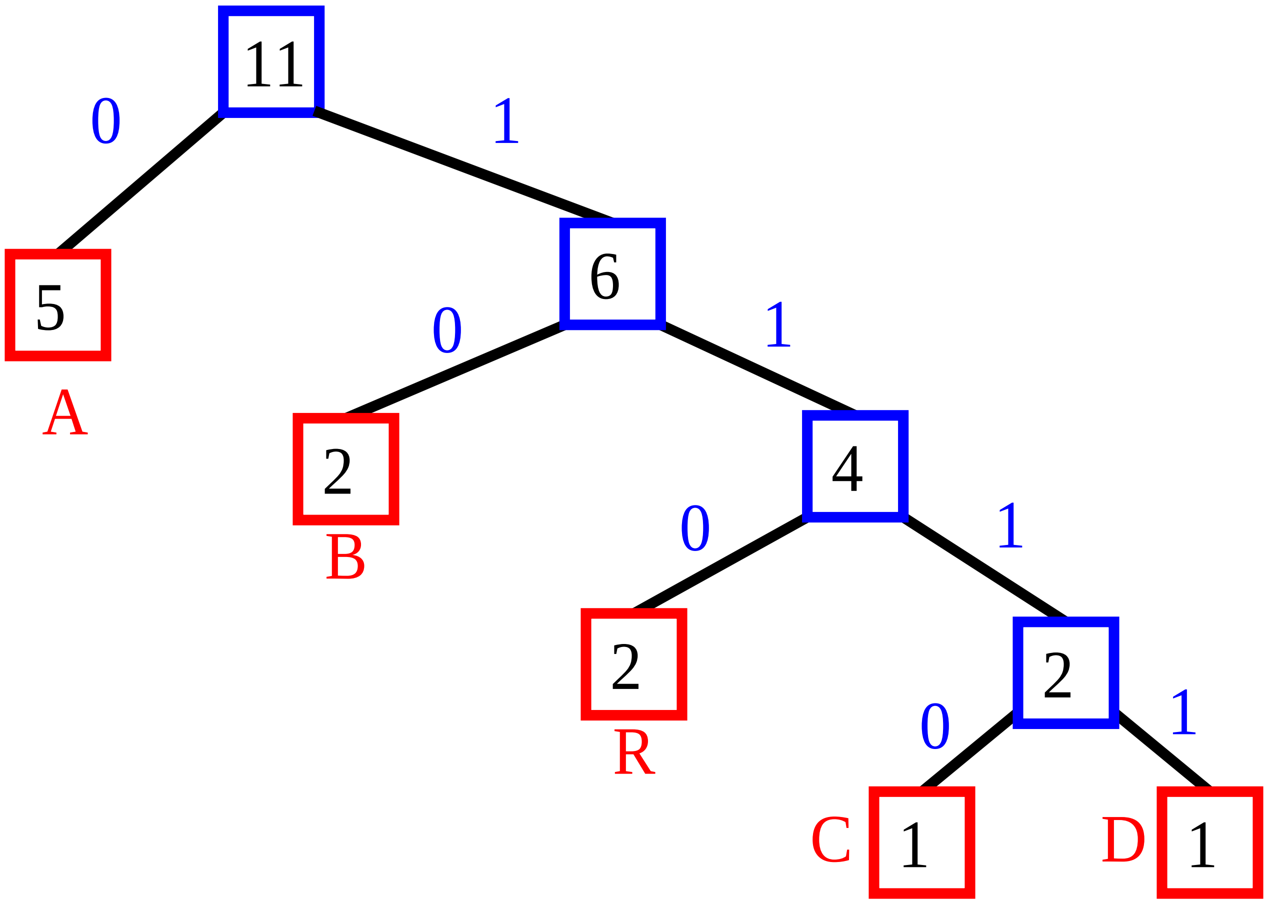



# Another Huffman Encoding Trie



# Another Huffman Encoding Trie




A B R A C A D A B R A

0 10 110 0 1100 0 1111 0 10 110 0

**23 bits**

# Construction Algorithm

- with a Huffman encoding trie, the encoded text has minimal length

**Algorithm** Huffman($X$):
**Input**: String $X$ of length $n$
**Output**: Encoding trie for $X$

Compute the frequency $f(c)$ of each character $c$ of $X$.
Initialize a priority queue $Q$.

**for** each character $c$ in $X$ **do**
    Create a single-node tree $T$ storing $c$
    $Q$.insertItem($f(c)$, $T$)
**while** $Q$.size() > 1 **do**
    $f_1 \leftarrow Q$.minKey()
    $T_1 \leftarrow Q$.removeMinElement()
    $f_2 \leftarrow Q$.minKey()
    $T_2 \leftarrow Q$.removeMinElement()
    Create a new tree $T$ with left subtree $T_1$ and right subtree $T_2$.
    $Q$.insertItem($f_1 + f_2$)
**return** tree $Q$.removeMinElement()

- runing time for a text of length n with k distinct characters: O(n + k log k)

# Image Compression

- we can use Huffman encoding also for binary files (bitmaps, executables, etc.)
- common groups of bits are stored at the leaves
- Example of an encoding suitable for b/w bitmaps