Abstract. The direct acyclic word graph (DAWG) is a good data structure representing a set of strings related to some word with very small space complexity. The famous DAWG is the factor DAWG which is representing the set Fac(text) of all factors (substrings) of the string text. Below we call factor DAWG as DAWG. Finite automaton implementing this data structure is able to make out any substring of string text in time proportional only to length of the substring while its space complexity is linear to the length of the string text. We can define several operations on DAWG. Operations are useful for fast deriving of the DAWG automaton from a similar one. This paper concern operation L-delete on factor graph DAWG and the relationship between deterministic and nondeterministic factor automaton.

Key words: DAWG, factor automaton, substring, pattern matching, fast searching

1 Introduction

The factor automaton is a finite automaton which accepts the set of all substrings of the string [1, chapter 6]. The set of all substrings (factors) of the string text is Fac(text).

This factor automaton can be formulated as a deterministic one or a nondeterministic one. The nondeterministic factor automaton is a good abstraction for formal description of its behaviour and of operations performed on it. On the other hand the deterministic one is used for implementation and practical use. This version is sometimes called direct acyclic word graph, DAWG, because it has no transition loop.

The main advantage of the DAWG is very fast substrings searching while it keeps small memory requirements. Any matching string can be found in time equal to the length of the pattern looking for. The size of the factor automaton DAWG(text) is linear with respect to the length of the string text. Total number of the nodes is less then double length of the input string text. The proof is in [1, Theorem 6.1].

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2 Construction

2.1 Nondeterministic factor automaton

The nondeterministic factor automaton, which accepts all substrings of the string \textit{text}, has \(N + 1\) states and \(2N - 1\) transitions, where \(N\) is the length of the string \textit{text}. The structure of this automaton for string \textit{text} = \(a_1a_2a_3a_4\ldots a_N\) is shown on the next picture.

2.2 Deterministic factor automaton

The deterministic factor automaton \(\text{DAWG}\) can be obtained from nondeterministic one or we can construct it step by step using an incremental construction algorithm [1, 6.3 On-line construction]. Although we have a construction algorithm, in general, we cannot say anything about the structure of transitions except nonexistence of the circle and an estimate bounds of the number of states. The pattern matching using this automaton has optimal speed. The number of comparations (or other elementar operations) is linear to the length of the searching pattern.

2.3 Relation between deterministic and nondeterministic automata

It appears that every construction method produces equivalent (isomorphic) deterministic factor automaton. We can say the deterministic factor automaton is the best simulation of the nondeterministic one. In this simulation every state in deterministic automaton corresponds to a set of active states in nondeterministic automaton. This relationship can be very useful for discovering and proving new algorithms for deterministic automata.

3 Operations on factor automaton

We can define a number of operations on factor automaton. Each operation modify given factor automaton representing string \textit{text} to a new factor automaton representing another string \textit{text}' while strings \textit{text} and \textit{text}' are very similar. It is important that both new and old factor automaton will be similar too and therefore performing the operation spend a little amount of time.

We will deal with this operations on a factor automaton:
### The algorithms for some operations have been yet discovered (`Append`, `R-delete`), but the algorithms of `Insert` and `Replace` are not known. This article concern about the algorithm of the `L-delete` operation.

This operation modifies DAWG($a_0a_1a_2a_3...a_n$) to another factor automaton accepting all substrings of the string $a_1a_2a_3...a_n$ which is by a first character $a_0$ shorter then the original string $a_0a_1a_2a_3...a_n$. The algorithm is shown bellow.

The combination of operations `Append` and `L-delete` enables fast searching in the compression method known as LZ77 which use so called sliding window. Sliding window contains a part of source text with constant length. The window is moving through the text so at the beginning it contains the first k characters of the text and at the end operating it contains the last k characters of the source text.

### DAWG in details

To enable incremental construction of this factor automata (`append` operations) requires to keep a bit more information about the DAWG working on. In every step we should know the set of states (a state of finite automaton per a node of the DAWG), transitions between the states (representing edges of the DAWG), and the fail function. The fail function is used for creating and extending DAWG. We will need know which is the next character for each state for the `L-delete` operation.

Before we will show the algorithm we should make some denotation. $\text{Next}(q)$ is a following character in source string $text$ for each state $q$ in the DAWG factor automaton. Concatenation of $\text{Next}(q_0) + \text{Next}(\text{Next}(q_0)) + ...$ gives the string $text$ for DAWG($text$). There is defined the fail function $\text{Fail}(q)$ for each state $q$ of DAWG automaton. If the automaton is in the state $q_1$ after reading substring $uv$ and in the state $q_2$ after reading substring $u$ which is the longest possible then $\text{Fail}(q_1)=q_2$.

Factor automaton being in state $q_2$ accepts each suffix which is accepted in state $q_1$. $\text{Skip}(q)$ is the set of states $p_i$ which $\text{Fail}(p_i)$ is equal to state $q$. Function $\text{Skip}$ is the inverse function of function $\text{Fail}$: $p \in \text{Skip}(q)$ iff $q = \text{Fail}(p)$.

### 5 The algorithm of L-delete operation

Let main chain is a sequence of states $q_0, q_1=\delta(q_0, \text{Next}(q_0)), ..., q_i=\delta(q_{i-1}, \text{Next}(q_{i-1})), ..., q_n$. The idea of this algorithm is to disable passing only through a part of the main chain but to protect passing anyway through at least one skip transition.

This algorithm duplicates the starting part of main chain of states. One copy (original) of begin of main chain is used for processing these substrings which will pass through some skip transition later. Second copy (duplicated) is used for processing these states which have passed some skip transition before.
Not all main chains will be duplicated. The duplication process stops at the state where is obvious which shift transition will be pass. This stop state is determined by a value of Skip function. Assume last duplicated state is $r$. Next state to be duplicate is $s$. Let state $t = \delta(s, \text{Next}(s))$ is the next state after $s$. If the set of states $\text{Skip}(t)$ is empty then duplication process stops, because no shift transition can be pass. If the set of states $\text{Skip}(t)$ contain only one state, then duplication process stops too, because only one shift transition is possible and therefore it can be done immediately. Otherway if the number of states $\text{Skip}(t)$ is greater then one then duplication process continue.

INPUT: DAWG(aw)
OUTPUT: DAWG(w)
LOCAL VARIABLES: $a$ - a character
$q_0$, $q_1$, $r$, $s$, $t$, $d$ - states
$q_0$ - the initial state

$$a := \text{Next}(q_0)$$
$$q_1 := \delta(q_0, a)$$
if $|\text{Skip}(q_1)| = 0$ then
$$\delta(q_0, a) := \text{nil}$$
$\text{delete}(q_1)$
else if $|\text{Skip}(q_1)| = 1$ then
$$\delta(q_0, a) := \text{Skip}(q_1)$$
$\text{delete}(q_1)$
else
$$r := q_0$$
$$s := q_1$$
loop
$$a := \text{Next}(s)$$
$$t := \delta(s, a)$$
if $|\text{Skip}(t)| < 2$ then break
$$d := \text{duplicate}(t)$$
$$\delta(r, a) := d$$
$$\text{Fail}(t) := d$$
$$r := d$$
$$s := t$$
endloop
if $|\text{Skip}(t)| = 1$ then
$$\delta(s, a) := \text{Skip}(t)$$
else
$$\delta(s, a) := \text{nil}$$
endif
6 Time and memory complexity

It seems that the time complexity of one \textit{L-delete} operation is at least constant or in the worst case linear to length of the text \textit{text}. The DAWG(\textit{text}) for string \textit{text} of length \(N\) has at most \(2 \times N\) states \([1]\). Therefore the time complexity of sequence of \(N\) \textit{L-delete} operations is linear to \(N\).

The number of states of DAWG(\textit{text}) is limited by \(2 \times N\) where \(N\) is number of characters in source string \textit{text}. Moreover, DAWG(\textit{text}) has less than \(3 \times N\) edges. This is independent of the size of the alphabet \([1\text{, Theorem 6.1]}\).

7 Conclusion

The power of operation \textit{L-delete} grows up in conjunction with the operation \textit{append}. We can apply \(k\)-times operation \textit{append} which constructs the base DAWG for first \(k\) characters of the text. Then we will apply repeatively a couple of operations \textit{L-delete} and \textit{append}. We will get a moving window for fast searching in this part of the text. The speed of searching is independent of size of the searching window and depends only on the size of pattern looking for. The main application can be LZ77 compression algorithm. The part consuming the largest amount of time is just the algorithm searching for a pattern in a searching window. Using this searching algorithm should speed up compression.

References

