Multi-Pattern String Matching with Very Large Pattern Sets

Leena Salmela

L. Salmela, J. Tarhio and J. Kytöjoki: Multi-pattern string matching with q-grams.
ACM Journal of Experimental Algorithmics, Volume 11, 2006.

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Outline

Problem Definition and Motivation

Previous Algorithms

Filtering Approach
    Verification
    Filtering

Experimental Results

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Problem Definition

Definition (Multiple pattern matching problem)

Given a pattern set P and a text t, report all occurrences of all the patterns in the text.

- The text t is a string of n characters drawn from the alphabet Σ (of size σ).
- The pattern set P is a set of r patterns each of which is a string of characters over the alphabet Σ.
- For simplicity we assume that all patterns have the same length m.
- We are especially interested in searching for large pattern sets ($>$10,000 patterns)

Why large pattern sets?

- Applications where large pattern sets are needed:
    - Antivirus scanning (around 100,000 known viruses)
    - Intrusion detection
    - Bioinformatics
- Older algorithms were not developed for such large pattern sets and they do not scale very well.

Outline

Trie-Based Algorithms

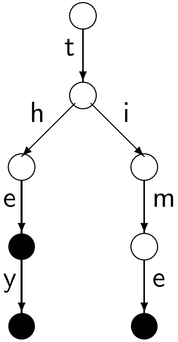

Figure: Trie built of the patterns "the", "they" and "time".

- Aho-Corasick, Commentz-Walter, SBOM etc.
- Many multi pattern algorithms build a trie of the patterns and search the text with the aid of the trie.
- The trie grows quite rapidly as the pattern set grows.
  - For $\sigma = 256$, $m = 8$ and 100,000 patterns the trie takes 500 MB of memory.

$\Longrightarrow$ Trie-based algorithms are not practical for large pattern sets.

Rabin-Karp (for Single Pattern)

Preprocessing

1. Compute a hash of the pattern $hs(p_0 ... p_{m-1})$

Searching

1. For each text position i compute the hash $hs(t_i ... t_{i+m-1})$
2. If the hash equals the hash of the pattern, verify the match.

Multiple Pattern Matching Based on Rabin-Karp

Preprocessing

1. Compute the hash of each pattern $hs(p^i_0 \ldots p^i_{m-1})$ and store them.
2. Sort the patterns according to the hash values.

Searching

1. For each text position i compute the hash $hs(t_i \ldots t_{i+m-1})$
2. Search for the hash value from the saved hash values of the patterns using binary search.
3. If the hash equals the hash of a pattern, verify the match.

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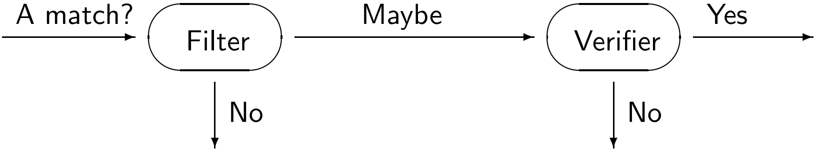
Filtering Approach



- Given a text position, a filter can tell if there cannot be a match at this position.
- The hashes in the (single pattern) Rabin-Karp algorithm act as a filter; If the hashes do not match there cannot be a match at that position.
- A good filter is fast and produces few false positives.
- A verifier is needed to distinguish between false and true positives.

Verification

- Verification of a single pattern is easy. (pairwise comparison)
- In a multiple pattern algorithm, the filter only tells some of the patterns might match
  $\Longrightarrow$ The verifier also needs to figure out which pattern to try.
- Using a trie would work but needs a lot of space (something we wanted to avoid in the first place)
- The verifier should be space-efficient and faster than pairwise comparison of all patterns against the given text position
  $\Longrightarrow$ Rabin-Karp for multiple patterns!

Character Class Filter

- Given a set of patterns...

p	a	t	t	e	r	n
f	i	l	t	e	r	s

Character Class Filter

- Given a set of patterns...
- ...construct a generalized pattern with character classes and apply any algorithm capable of handling such generalized patterns.

p a t t e r n
f i l t e r s

↓

[f,p] [a,i] [l,t] [t] [e] [r] [n,s]

Character Class Filter

- Given a set of patterns...
- ...construct a generalized pattern with character classes and apply any algorithm capable of handling such generalized patterns.
- How to make it work with very large pattern sets?

p a t t e r n
f i l t e r s

↓

[f,p] [a,i] [l,t] [t] [e] [r] [n,s]

Character Class Filter with *q*-Grams

- Given a set of patterns...
- ...construct a generalized pattern with character classes and apply any algorithm capable of handling such generalized patterns.
- How to make it work with very large pattern sets?
  - Use superalphabets (q-grams)

p a t t e r n → pa at tt te er rn

f i l t e r s → fi il lt te er rs

Character Class Filter with *q*-Grams

- Given a set of patterns...
- ...construct a generalized pattern with character classes and apply any algorithm capable of handling such generalized patterns.
- How to make it work with very large pattern sets?
  - Use superalphabets (q-grams)
  - ...and construct a generalized pattern.

p a t t e r n → pa at tt te er rn
f i l t e r s → fi il lt te er rs

↓

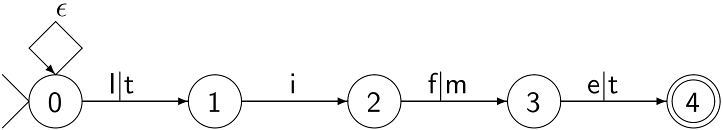
[fi,pa] [at,il] [lt,tt] [te] [er] [rn,rs]

Character Class Filters

- The character class filter is truly a filter
    - It recognizes any occurrence of the pattern.
    - False positives are also found. (I.e. “filtern” and “patters” are recognized by the filter on the previous slide.)
- We have implemented the filter with three different character class algorithms:
    - Multi-Pattern Horspool with q-Grams (HG)
        - A Boyer-Moore-Horspool type algorithm
    - Multi-Pattern Shift-Or with q-Grams (SOG)
        - Shift-Or (simplest, presented in following slides)
    - Multi-Pattern BNDM with q-Grams (BG)
        - BNDM (average optimal for $q = O(\log_\sigma r)$, fastest in practise)

Shift-Or Character Class Filter

- Suppose we are searching for patterns “lift” and “time” so the character class pattern is “[l,t][i][f,m][e,t]”.
- The following NFA finds all occurrences of the character class pattern:



- The shift-or algorithm is a bit-parallel simulation of this automaton.

Shift-Or Character Class Filter: Preprocessing

- For each character c of the alphabet, initialize a bit vector $T[c]$ such that the i'th bit is 0 iff the character appears in any of the patterns in position i.
- In our example (patterns "lift" and "time"):

T['e']	0111
T['f']	1011
T['i']	1101
T['l']	1110
T['m']	1011
T['t']	0110

- The automaton has a transition from state i to state $i + 1$ on character c iff i:th bit in $T[c]$ is 0.

Shift-Or Character Class Filter: Searching

- State vector E where i'th bit is 0 iff state i in the automaton is active.
- Initialize E as 1111.
- Update E when a character c is read from the text:

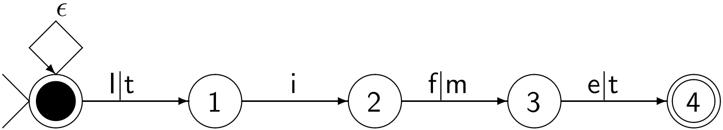
$$E = (E \ll 1) \mid T[c]$$

- After the update, i'th bit in E is 0 iff $i-1$:th bit was 0 (the previous state $i-1$ was active) and i'th bit is 0 in $T[c]$ (there is a transition from state $i-1$ to i on c).

Shift-Or Character Class Filter: Searching

Matching against the text: “ttime”

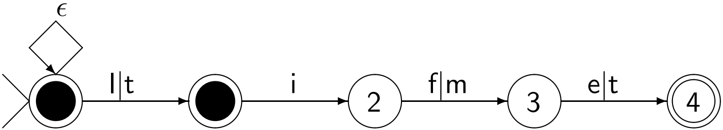
E = 1111



Shift-Or Character Class Filter: Searching

Matching against the text: “ttime”

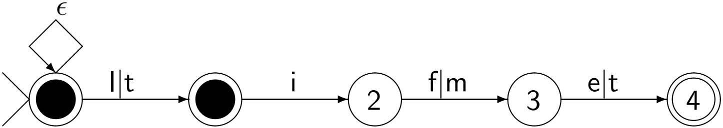
$$\begin{array}{ll} & E = 1111 \\ \text{Read 't'} & E = (1111 \ll 1) \mid 0110 = 1110 \end{array}$$



Shift-Or Character Class Filter: Searching

Matching against the text: “ttime”

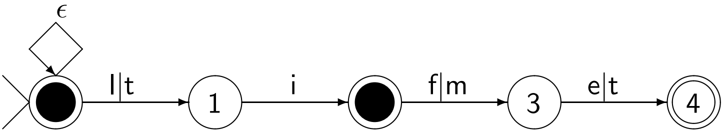
	E = 1111
Read ’t’	E = (1111 ≪ 1) | 0110 = 1110
Read ’t’	E = (1110 ≪ 1) | 0110 = 1110



Shift-Or Character Class Filter: Searching

Matching against the text: “ttime”

$$\begin{array}{ll} & E = 1111 \\ \text{Read 't'} & E = (1111 \ll 1) \mid 0110 = 1110 \\ \text{Read 't'} & E = (1110 \ll 1) \mid 0110 = 1110 \\ \text{Read 'i'} & E = (1110 \ll 1) \mid 1101 = 1101 \end{array}$$



Shift-Or Character Class Filter: Searching

Matching against the text: “ttime”

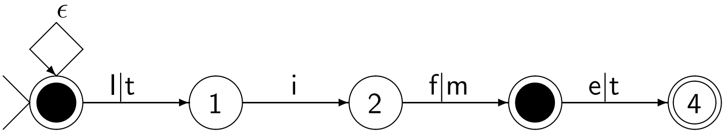
$E = 1111$

Read 't' $E = (1111 \ll 1) \mid 0110 = 1110$

Read 't' $E = (1110 \ll 1) \mid 0110 = 1110$

Read 'i' $E = (1110 \ll 1) \mid 1101 = 1101$

Read 'm' $E = (1101 \ll 1) \mid 1011 = 1011$



Shift-Or Character Class Filter: Searching

Matching against the text: “ttime”

$E = 1111$

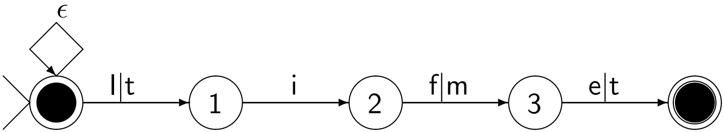
Read 't' $E = (1111 \ll 1) \mid 0110 = 1110$

Read 't' $E = (1110 \ll 1) \mid 0110 = 1110$

Read 'i' $E = (1110 \ll 1) \mid 1101 = 1101$

Read 'm' $E = (1101 \ll 1) \mid 1011 = 1011$

Read 'e' $E = (1011 \ll 1) \mid 0111 = 0111$



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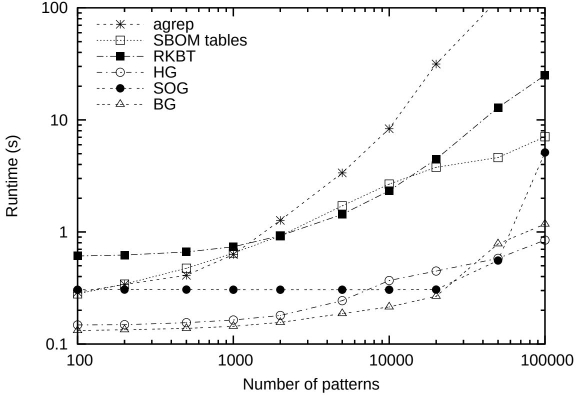
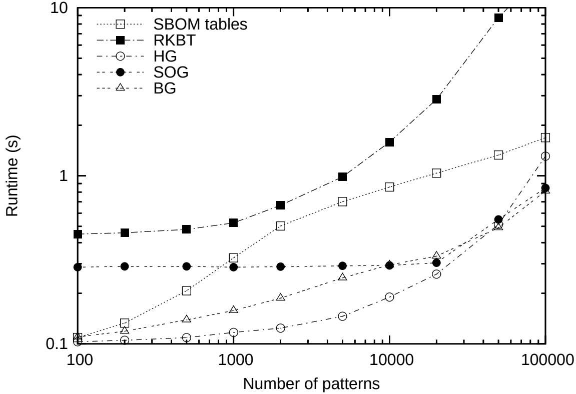


$m = 8$, $\sigma = 256$, random data, $q = 2...3$

Experimental Results



$m = 32$, $\sigma = 4$, DNA data (chromosome from fruitfly genome), $q = 6 \ldots 10$

Summary

- Trie-based approaches not practical with very large pattern sets
- Filtering approach to multiple pattern matching
  - Transform patterns to sequences of q-grams
  - Filter with a character class pattern built from the transformed pattern set
  - Verify with a Rabin-Karp style algorithm