Multi-Pattern String Matching with Very Large Pattern Sets

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Outline

Problem Definition and Motivation

Previous Algorithms

Filtering Approach
  Verification
  Filtering

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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 $\Sigma$ (of size $\sigma$).
- The pattern set $P$ is a set of $r$ patterns each of which is a string of characters over the alphabet $\Sigma$.
- 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.
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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.

$\implies$ 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 $hs(p_0^i...p_{m-1}^i)$ and store them.
2. Sort the patterns according to the hash values.

Searching

1. For each text position $i$ compute the hash $hs(t_i...t_{i+m-1})$
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
  \[\implies\] 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
  \[\implies\] Rabin-Karp for multiple patterns!
Character Class Filter

- Given a set of patterns...
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.

```
pattern filters
↓
[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?

\[
p a t t e r n \\
\text{f i l t e r s} \\
\downarrow \\
[f,p] \quad [a,i] \quad [l,t] \quad [t] \quad [e] \quad [r] \quad [n,s]
\]
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)

\[
\text{pattern} \rightarrow \text{pattern} \\
\text{filters} \rightarrow \text{filters}
\]
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.

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

\[
\downarrow
\]

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

```
0 ---- l|t ----> 1 ---- i ---- 2 ---- f|m ---- 3 ---- e|t ---- 4
```

- 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”):
  
  \[
  \begin{align*}
  T[\text{'e'}] & \quad 0111 \\
  T[\text{'f'}] & \quad 1011 \\
  T[\text{'i'}] & \quad 1101 \\
  T[\text{'l'}] & \quad 1110 \\
  T[\text{'m'}] & \quad 1011 \\
  T[\text{'t'}] & \quad 0110
  \end{align*}
  \]
- 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:
  \[
  E = (E \ll 1) \lor T[c]
  \]
- 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”

\[ E = 1111 \]

Read ’t’ \[ E = (1111 \ll 1) | 0110 = 1110 \]
Shift-Or Character Class Filter: Searching

Matching against the text: “ttime”

\[ E = 1111 \]

Read 't' \[ E = (1111 \ll 1) | 0110 = 1110 \]

Read 't' \[ E = (1110 \ll 1) | 0110 = 1110 \]
Shift-Or Character Class Filter: Searching

Matching against the text: “ttime”

\[ E = 1111 \]

Read ′t′ \[ E = (1111 \ll 1) | 0110 = 1110 \]

Read ′t′ \[ E = (1110 \ll 1) | 0110 = 1110 \]

Read ′i′ \[ E = (1110 \ll 1) | 1101 = 1101 \]
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”

\[
\begin{align*}
E &= 1111 \\
\text{Read ‘t’} & \quad E = (1111 \ll 1) \mid 0110 = 1110 \\
\text{Read ‘t’} & \quad E = (1110 \ll 1) \mid 0110 = 1110 \\
\text{Read ‘i’} & \quad E = (1110 \ll 1) \mid 1101 = 1101 \\
\text{Read ‘m’} & \quad E = (1101 \ll 1) \mid 1011 = 1011 \\
\text{Read ‘e’} & \quad E = (1011 \ll 1) \mid 0111 = 0111
\end{align*}
\]
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$m = 8, \sigma = 256, \text{random data, } q = 2...3$
**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