An Overview of Cache Optimized FA-based String Processors

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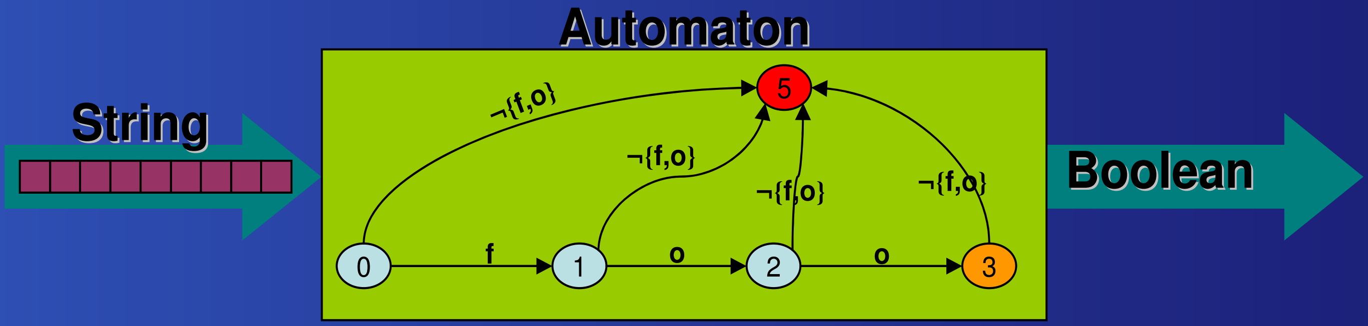
Agenda

1. Introduction
2. Cache optimized algorithms
3. Spectrum of the algorithms
4. Taxonomy and toolkit
5. Applications

Introduction: The Problem

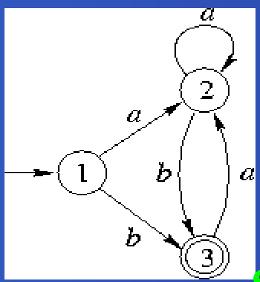
Given an automaton $\mathcal{M} = (\mathcal{V}, \mathcal{Q}, s_0, \mathcal{F}, \delta)$ and a string s

- Determine whether s is part of the language $\mathcal{L}$ modeled by $\mathcal{M}$



The table-driven (TD) algorithm

A 2D array is used to hold δ before scanning



Symbol

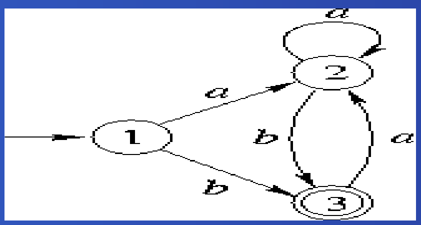
δ state	a	b
1	2	3
2	2	3
3	2	-1

```
#define isFinal(s)      ((s) < 0)
int scanner()
{  char ch;
   int currState = 1;

   while (TRUE) {
      ch = NextChar( );
      if (ch == EOF) return 0;  /* fail */
      currState = δ[currState, ch];
      if (IsFinal(currState)) {
         return 1;  /* success */
      }
   } /* while */
}
```

The hardcoded (HC) algorithm

δ forms part of the algorithm



```
#define isFinal(s)       ((s) < 0)
int scanner()
{  char ch;
   int s = 1;
   while (TRUE) {
      ch = NextChar( );
     if (ch==EOF) return 0 /*fail*/
      if (s==1)
      {
         if (ch=='a') s = 2
         else s = 3
        }
      else if (s==2)...
       ....
       if (IsFinal(s)) return 1;  /*success */
} /* while */
}
```

Limitations of TD and HC

- Performance is hampered by the memory/instruction load problem
  - As the automaton size grows, more memory required

- The random access nature of the table/states is a performance bottleneck
  - Cache misses penalties occur since states information are not well organized

- Weak in processing large strings based on large automata

Cache optimized algorithms

Dynamic State Allocation (DSA)

- Predefined portion of memory used for recognition
- A state out the predefined memory is first copied-in before recognition
    - Can be unbounded (no restriction on the size of the predefined memory)
    - Can be bounded (number of states to be allocated restricted)
- Efficient for recognizing large strings

Cache optimized algorithms

State pre-Ordering (SpO)

- States are reordered based on some previous processing history
- New states positions are kept in an auxiliary array
  - The array enables access to states' information
- Frequently accessed states are grouped together
  - Improves spatial and temporal locality of reference

Cache optimized algorithms

Allocated Virtual Caching (AVC)

- A portion of memory occupied by states is dedicated for acceptance testing
- The dedicated memory behaves as a cache (virtual)
    - Access policy: Direct and associative mapping ...
- Frequently accessed states are grouped together
    - Improves spatial and temporal locality of reference
- Efficient for large string visiting a limited set of states

Recognizer’s Denotational Semantics

Given an automaton $M(\mathcal{Q}, \mathcal{V}, \Delta, \mathcal{F}, s_0)$;
ρ is the string recognizer that maps (Δ, s) to a boolean

We assume the transition set Δ *is split into two disjoints subsets* Δ_t *and* Δ_h*:*

- Δ_t (resp. Δ_h) is the transition set for TD (resp. HC)

The following relationship holds $\forall s \in \mathcal{V}^*$:

$$\rho(\Delta, s) = \rho_{_C}(\Delta_t, \Delta_h, s) = \rho_{_C}(\Delta_t, \emptyset, s) = \rho_{_C}(\emptyset, \Delta_h, s)$$

- $\rho(\Delta, s) = \rho_{_C}(\Delta_t, \Delta_h, s)$ is the mixed-mode (MM) algorithm

Characterization of a Recognizer

A string recognizer of an FA can now be defined as an algorithm that maps its input string, its transition sets, and its associated strategy variables to a boolean:
Assume $\mathcal{T} = \mathcal{P}(\mathcal{Q} \times \mathcal{V} \times \mathcal{Q})$ *(transition relation)*

D_t *and* D_h *are natural numbers associated to DSA*
P_t *and* P_h *are boolean values associated to SpO*
V_t *and* V_h *are natural numbers associated to AVC*

Characterization of a Recognizer

$$\rho_N : \mathcal{T} \times \mathcal{T} \times \mathbb{N} \times \mathbb{N} \times \mathbb{B} \times \mathbb{B} \times \mathbb{N} \times \mathbb{N} \times \mathcal{V}^* \rightarrow \mathbb{B}$$

$$\rho_N(\Delta_t, \Delta_h, D_t, D_h, P_t, P_h, V_t, V_h, s) = \begin{cases} \text{T} & \text{if } s \in \mathcal{L}(\mathcal{M}) \\ \text{F} & \text{if } s \notin \mathcal{L}(\mathcal{M}) \end{cases}$$

Such that

$$\rho_N(\Delta_t, \Delta_h, D_t, D_h, P_t, P_h, V_t, V_h, s) = \rho(\Delta, s)$$

Characterization of a Recognizer

Formalisms with special values assigned to parameters:

- TD formalism: $\rho_{_N}(\Delta_t, \emptyset, D_t, 0, P_t, \mathsf{F}, V_t, 0, s)$
- HC formalism: $\rho_{_N}(\emptyset, \Delta_h, 0, D_h, \mathsf{F}, P_h, 0, V_h, s)$
- MM formalism: $\rho_{_N}(\Delta_t, \Delta_h, D_t, D_h, P_t, P_h, V_t, V_h, s)$

♣ **Specialized notations:**

- TD: $\rho_{_N}(\Delta_t, \emptyset, D_t, 0, P_t, \mathsf{F}, V_t, 0, s) = \rho_t(\Delta_t, D_t, P_t, V_t, s)$
- HC: $\rho_{_N}(\emptyset, \Delta_h, 0, D_h, \mathsf{F}, P_h, 0, V_h, s) = \rho_h(\Delta_h, D_h, P_h, V_h, s)$
- MM: $\rho_{_M}(\Delta_t, \Delta_h, D_t, D_h, P_t, P_h, V_t, V_h, s)$

Spectrum of the Algorithms (TD/HC)

- DSA Strategy: The variable $D_{t/h} \in \{0, d_{t/h}, |\mathcal{Q}_{t/h}|\}$; $d_{t/h} < |\mathcal{Q}_{t/h}|$
- SpO Strategy: The variable $P_{t/h} \in \{\texttt{T},\texttt{F}\}$
- AVC Strategy: The variable $V_{t/h} \in \{0, v_t\}$; $v_{t/h} < |\mathcal{Q}_{t/h}|$
- Resulting in $3 \times 2 \times 2 = 12$ different algorithms

Spectrum of the Algorithms (TD/HC)

Combination	Active strategy	TD/HC Name
$(0, \mathsf{F}, 0)$	None (core TD/HC)	t/h
$(d_{t/h}, \mathsf{F}, 0)$	bounded DSA	t/h_{b1}
$(n, \mathsf{F}, 0)$	unbounded DSA	t/h_{u1}
$(0, \mathsf{T}, 0)$	SpO	t/h_2
$(0, \mathsf{F}, v_{t/h})$	AVC	t/h_3
$(0, \mathsf{T}, v_{t/h})$	SpO and AVC	t/h_{23}
$(d_{t/h}, \mathsf{T}, 0)$	bounded DSA and SpO	t/h_{b12}
$(d_{t/h}, \mathsf{T}, v_{t/h})$	bounded DSA, SpO and AVC	t/h_{b123}
$(d_{t/h}, \mathsf{F}, v_{t/h})$	bounded DSA and AVC	t/h_{b13}
$(n, \mathsf{T}, 0)$	unbounded DSA and SpO	t/h_{u12}
$(n, \mathsf{T}, v_{t/h})$	unbounded DSA, SpO and AVC	t/h_{u123}
$(n, \mathsf{F}, v_{t/h})$	unbounded DSA and AVC	t/h_{u13}

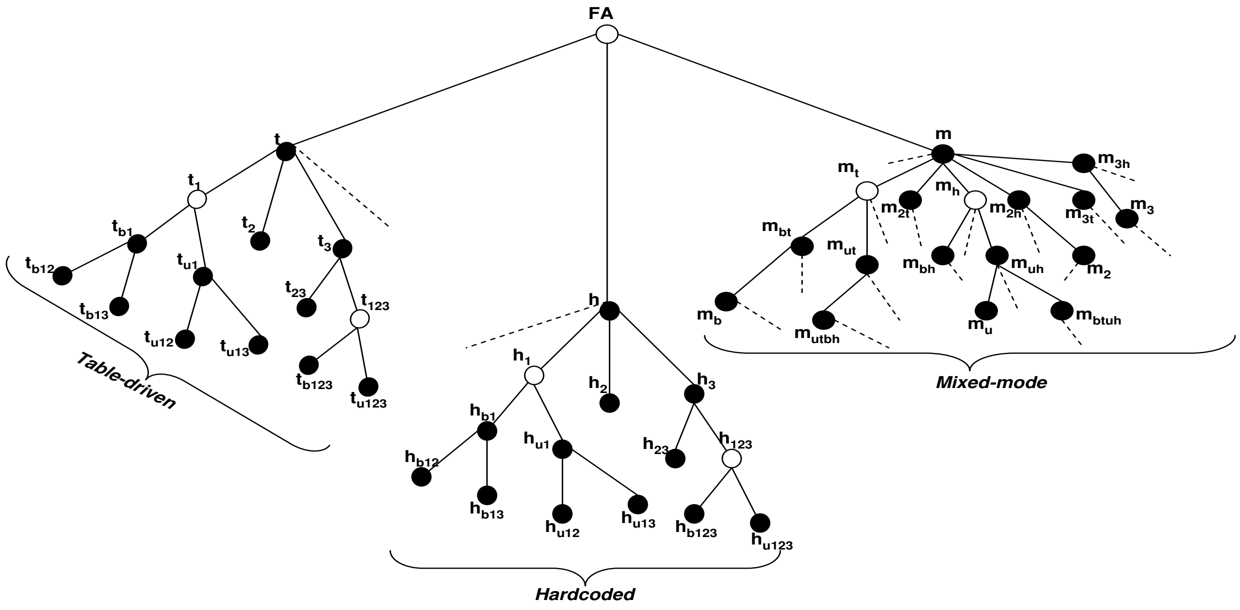
Spectrum of the Algorithms (MM)

- DSA Strategy: The variable $D_t \in \{0, d_t, |\mathcal{Q}_t|\}$, $d_t < |\mathcal{Q}_t|$; $D_h \in \{0, d_h, |\mathcal{Q}_h|\}$, $d_h < |\mathcal{Q}_h|$
- SpO Strategy: The variable $P_t \in \{\texttt{T}, \texttt{F}\}$; $P_h \in \{\texttt{T}, \texttt{F}\}$
- AVC Strategy: The variable $V_t \in \{0, v_t\}$, $v_t < |\mathcal{Q}_t|$; $V_h \in \{0, v_h\}$, $v_h < |\mathcal{Q}_h|$
- Resulting in $3 \times 3 \times 2 \times 2 \times 2 \times 2 = 144$ different algorithms

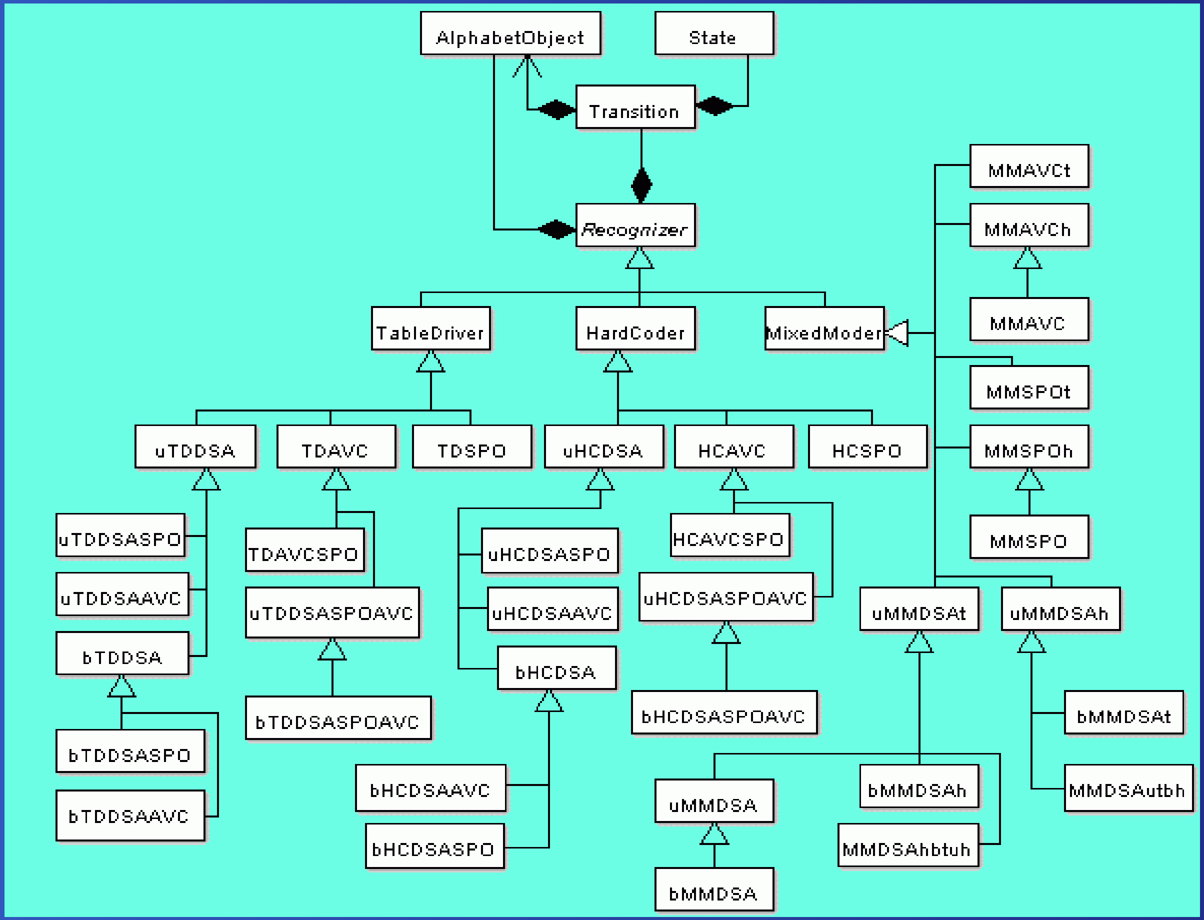
Spectrum of the Algorithms (MM)

MM formalism	Active strategies	MM Name
$(0, 0, F, F, 0, 0, s)$	None	m
$(0, d_h, F, F, 0, 0, s)$	bounded DSA on HC	m_{bh}
$(0, \|\mathcal{Q}_h\|, F, F, 0, 0, s)$	unbounded DSA on HC	m_{uh}
$(d_t, 0, F, F, 0, 0, s)$	bounded DSA on TD	m_{bt}
$(d_t, d_h, F, F, 0, 0, s)$	bounded DSA on TD and HC	m_b
$(d_t, \|\mathcal{Q}_h\|, F, F, 0, 0, s)$	bounded TD-DSA and unbounded HC-DSA	m_{btuh}
$(\|\mathcal{Q}_t\|, 0, F, F, 0, 0, s)$	unbounded DSA on TD	m_{ut}
$(\|\mathcal{Q}_t\|, d_h, F, F, 0, 0, s)$	unbounded TD-DSA and bounded HC-DSA	m_{utbh}
$(\|\mathcal{Q}_t\|, \|\mathcal{Q}_h\|, F, F, 0, 0, s)$	unbounded DSA on TD and HC	m_u
$(0, 0, T, T, 0, 0, s)$	SPO on TD and HC	m_2
$(0, 0, T, F, 0, 0, s)$	SPO on TD	m_{2t}
$(0, 0, F, T, 0, 0, s)$	SPO on HC	m_{2h}

A taxonomy graph



The Toolkit: An extract class-diagram



Applications: NLP

1. *Efficient Dictionary representation*
    - Very fast implementation based on FAs
2. *Morphological Analysis*
    - FA-based Morphotactics
    - FA-based Segmentation (Approximate PM)
    - FA-based N-gram analysis (?)
3. *Acoustic Analysis*
    - Related to Morphology(but now Phonetic)
4. *Part-Of-Speech Tagging*

Applications: Genomic/DNA Analysis

1. *Efficient for **short** DNA representation*
    - Only 4 alphabet symbols ($ACGT$)
2. *Challenge in general genomic*
    - DNA sequence very long (Text unknown in advance)
    - Pattern to investigate unknown (for Virus scanning)
3. Current MSc exercise
    - FA-based DNA Analysis

Applications

Network Intrusion Detection

1. *Efficient for pattern matching*
    - Predefined alphabet symbol set
    - known frequently used symbols (SpO?)

Questions?