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Characterization of Finite Automata Implementations: A Preliminary Taxonomy

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Characterization of FAs Implementations

Agenda

- Background and Motivations
- Characterization of Finite Automata
- Characterization of Acceptors
- Constraints Identification: Refining the Characterization
- Deriving the kwk Algorithms
- A Preliminary Taxonomy Tree
- Future Work

Background and Motivations

- Two Finite Automata Implementation Approaches
  - Conventional: Table-driven Algorithm
    - Memory load problems (transition matrix)
    - Limited capacity of data cache
  - Alternative: Hardcoded Algorithm
    - Regular expressions (Thompson-1968)
    - Pattern Matching (Knuth -1977)
    - Instructions load problems
    - Limited capacity of instruction cache

Background and Motivations

- Need to explore other strategies in order to:
  - To reduce memory load
    - Dynamic data (states) allocation in memory
  - To reduce instruction load
    - Dynamic instructions (states) allocation in memory
  - To exploit hardware's capabilities:
    - Cache structure and principles
      - Cache mapping and replacement principles
      - Cache locality of reference
      - Unified cache / Split cache

Characterization of Finite Automata

- A Finite Automaton M is a 5-tuple (s_0,Q,F,Σ,δ) where:
  - s_0 is the initial state
  - Q is the set of states ($s_0 \in Q$)
  - F the set of final states ($F \subseteq Q$)
  - Σ the set of alphabet symbols
  - δ the transition function

Characterization of Finite Automata

- $\delta: Q x \Sigma \rightarrow Q$
  $\delta(q_i,c) = q_j$
- Define the transition set $\Delta \subseteq Q x \Sigma x Q$
  - Elements of Δ are triplets of he form (q_i,c, q_j)
  - $\Delta \in \mathbf{P}(Q x \Sigma x Q)$: power set of $Q x \Sigma x Q$
  - $|Q|$ = number of states of M
- Define Σ^*, the set of all strings of Σ
  - **L** (M) is the set of all string accepted by M
  - **L** (M) $\subseteq \Sigma^*$
  - S $\in$ **L** (M) $\Leftrightarrow$ S $\in \Sigma^*$

Characterization of Acceptors

- An acceptor is a string recognizer that uses FA
- Define B = {`true`, `false`} the Boolean set; $b \in B$, a Boolean value
- $r: (Q \times \Sigma \times Q) \times \Sigma^* \rightarrow B$

  $r(\Delta, S) = b$

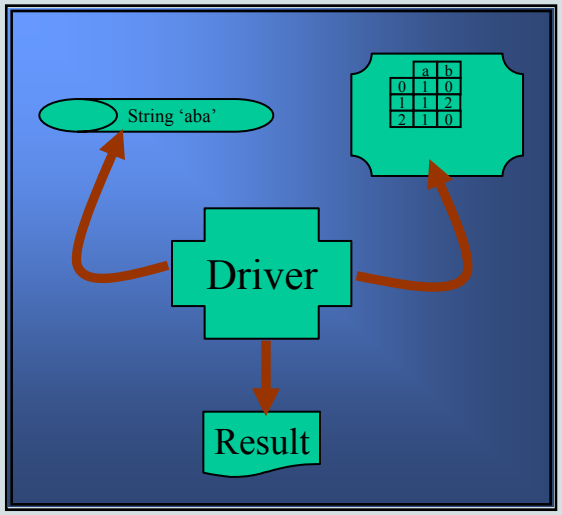
  - $r(\Delta, S) = \text{true} \Leftrightarrow S \in L(M)$
  - $r(\Delta, S) = \text{false} \Leftrightarrow S \notin L(M)$

Characterization of FAs Implementations

Characterization of Acceptors:

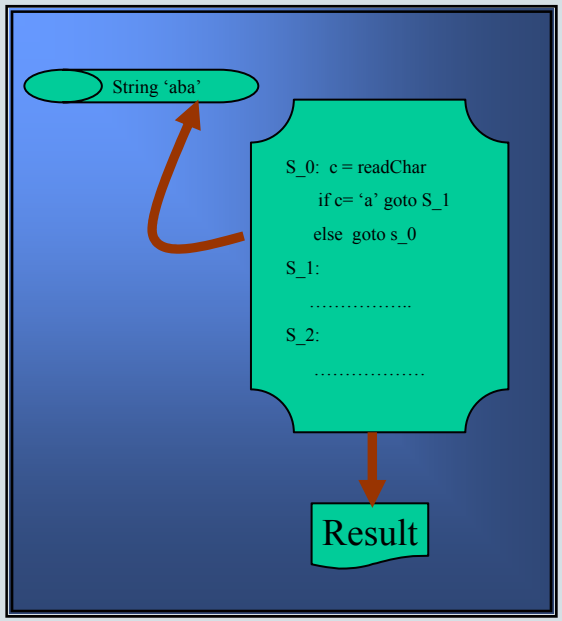
Implementation of $r_{(\Delta,S)}$

- Table driven: Driver + Transition matrix
  - Δ implemented as Δ_t
  - $r_{(\Delta,S)} \equiv r_{(\Delta_t,S)}$



Characterization of Acceptors: Implementation of $r(\Delta,S)$

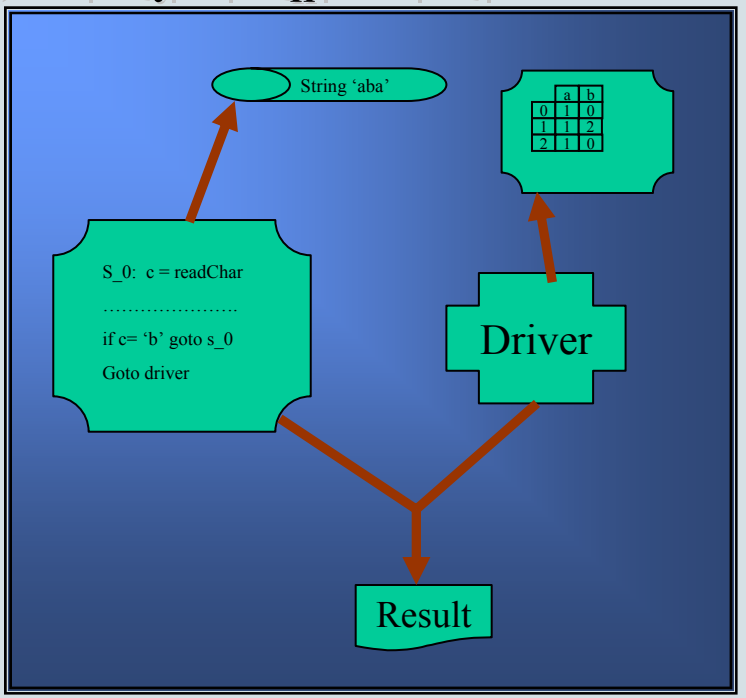
- Hardcoded: Instructions only
  - Δ implemented as Δ_h
  - $r(\Delta,S) \equiv r(\Delta_h,S)$



Characterization of FAs Implementations

Characterization of Acceptors: Implementation of $r(\Delta,S)$

- Mixed-Mode: Driver+Matrix +Instructions
  - $r(\Delta_t \cup \Delta_h,S) \equiv r'(\Delta_t,\Delta_h,S) : |Q_t|+|Q_h| = |Q|$



Constraints Identification: Refining the Characterization

- Consider $r(\Delta_t,\Delta_h,S)$: $|Q_t| + |Q_h| = |Q|$
  - This approach is somewhat general
  - It can be specialized in terms of constraints on
    - States
      - How many are hardcoded?
      - How many are in table?
      - How states are organized?
      - Etc
    - Provides various implementation strategies
      - Strategies or constraints become part of the characterization

Characterization of FAs Implementations

Constraints Identification: Dynamic Auxiliary Automaton (C_1)

- Acceptance is made using a Dynamic Auxiliary Automaton
  - Created at runtime
  - Function to the string path
  - States renamed in a new memory location
- C_1 is a Boolean in the characterization
  - C_{1t}: Dynamic Auxiliary Table
  - C_{1h} : Dynamic Auxiliary Hardcode
- New Characterization: $r_1(\Delta_t,\Delta_h,S,C_{1t},C_{1h})$: $|Q_t| + |Q_h| = |Q|$
  - TD: $r_1(\Delta_t,\phi,S,t,f)$: $|Q_t| = |Q|$
  - HC: $r_1(\phi,\Delta_h,S,f,t)$: $|Q_h| = |Q|$
- TD and HC use C_1 independently in mixed-mode

Characterization of FAs Implementations

Constraints Identification: State Ordering (C_2)

- States are organized on a predefined order before acceptance testing
  - Done before acceptance testing
  - Uses a profiler to define the ordering policy
    - e.g: Frequently used states are put together
- C_2 is a Boolean in the characterization
  - C_{2t}: States in the table are ordered
  - C_{2h} : Hardcoded states are ordered
- New Characterization: $r_2(\Delta_t,\Delta_h,S,C_{2t},C_{2h})$: $|Q_t| + |Q_h| = |Q|$
  - TD: $r_2(\Delta_t, \phi,S,t,f)$ $|Q_t| = |Q|$
  - HC : $r_2(\phi,\Delta_h,S,f,t)$ $|Q_h| = |Q|$
- TD and HC use C_2 independently in Mixed-mode

Constraints Identification: State Swapping (C_3)

- States are swapped between one another
  - Done at runtime
  - Uses a policy such as LRU to interchange states position
- C_3 is a Boolean in the characterization
  - C_{3t}: Table-driven states are swapped
  - C_{3h}: hardcoded states are swapped
- New Characterization: $r_3(\Delta_t,\Delta_h,S,C_{3t},C_{3h})$: $|Q_t| + |Q_h| = |Q|$
  - TD: $r_3(\Delta_t,\phi,S,t,f)$: $|Q_t| = |Q|$
  - HC: $r_3(\phi,\Delta_h,S,f,t)$: $|Q_h| = |Q|$
- TD and HC use C_3 independently in Mixed-mode

Constraints Identification: State Caching (C_4)

- A space in memory referred to as "cache" is predefined with a number of states
  - Space allocated with states before acceptance testing
  - Acceptance testing only happens within the predefined "cache"
  - Uses a policy such as LRU to allocate new states in "cache"
- C_4 is a natural number: $C_4 \leq |Q|$
  - $C_4 = 0$ means there is no states caching
  - C_{4t}: Table-driven states use a predefined "Cache"
  - C_{4h}: Hardcoded states use a predefined "Cache"
- New Characterization: $r_4(\Delta_t,\Delta_h,S,C_{4t},C_{4h})$: $|Q_t| + |Q_h| = |Q|$
  - TD: $r_4(\Delta_t, \phi,S,m,0)$ $|Q_t| = |Q|$, $m \leq |Q|$
  - HC: $r_4(\phi,\Delta_h,S,0,m)$ $|Q_h| = |Q|$, $m \leq |Q|$
- TD and HC use C_4 independently in Mixed-mode; $C_{4t} + C_{4h} \leq |Q|$
- If C_5 is set and $C_4 = C_5$, then Dynamic allocation occurs within the "cache"

Constraints Identification: Dynamic State Allocation (C_5)

- States are allocated dynamically in memory at runtime before acceptance testing
  - This is a JIT like processing of acceptors
  - Acceptance testing only happens within the dynamically allocated space
  - States are not renamed in the newly allocated space
  - State allocation depends on the string path
- C_5 is a natural number: $C_5 \leq |Q|$
  - $C_5 = 0$ means there is no states caching
  - C_{5t}: Table-driven states are dynamically allocated during acceptance testing
  - C_{5h}: Hardcoded states are dynamically allocated during acceptance testing
- New Characterization: $r_4(\Delta_t,\Delta_h,S,C_{5t},C_{5h})$: $|Q_t| + |Q_h| = |Q|$
  - TD: $r_4(\Delta_t, \phi,S,m,0)$ $|Q_t| = |Q|$, $m \leq |Q|$
  - HC: $r_4(\phi,\Delta_h,S,0,m)$ $|Q_h| = |Q|$, $m \leq |Q|$
- TD and HC use C_4 independently in Mixed-mode; $C_{4t} + C_{4h} \leq |Q|$
- If C_4 is set and $C_4 = C_5$, then Dynamic allocation occurs within the "cache"

Constraints Identification: Generalization

- Without lost of generality, we define

$$r(\Delta_t,\Delta_h,S, C_{1t},C_{1h},C_{2t},C_{2h},C_{3t},C_{3h},C_{4t},C_{4h},C_{5t},C_{5h})$$

$$|Q_t| + |Q_h| = |Q| \; ; \; C_{4t} + C_{4h} \leq |Q| \; ; \; C_{5t} + C_{5h} \leq |Q|$$

- Many algorithms can be derived
  - Some may not be useful in practice

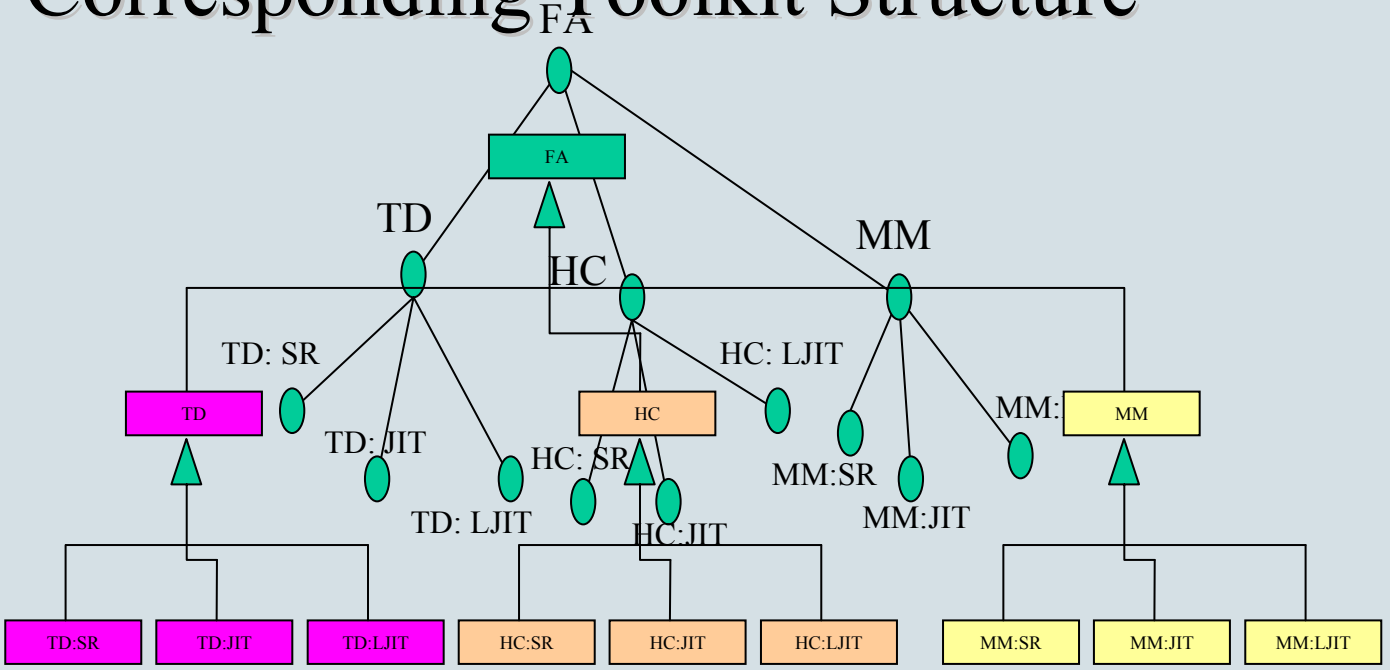
Characterization of FAs Implementations

Deriving the kwk Algorithms

kwk algorithms

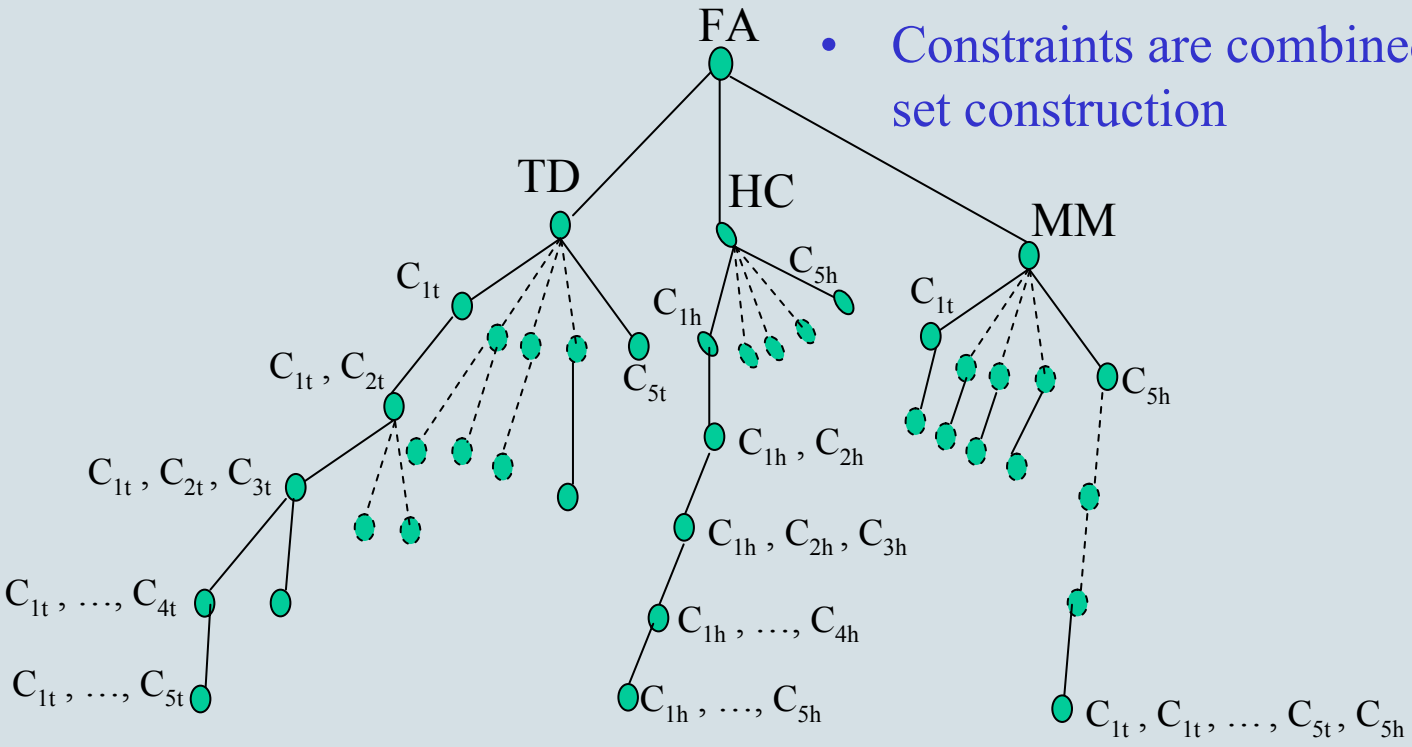
	Δ_t	Δ_h	C_{1t}	C_{1h}	C_{2t}	C_{2h}	C_{3t}	C_{3h}	C_{4t}	C_{4h}	C_{5t}	C_{5h}
TD	Δ_t	ϕ	F	F	F	F	F	F	0	0	0	0
HC	ϕ	Δ_h	F	F	F	F	F	F	0	0	0	0
SR:TD	Δ_t	ϕ	T	F	F	F	F	F	0	0	0	0
SR:HC	ϕ	Δ_h	F	T	F	F	F	F	0	0	0	0
MM	Δ_t	Δ_h	F	F	F	F	F	F	0	0	0	0
HC:JIT	ϕ	Δ_h	F	F	F	F	F	F	0	0	0	$\lvert Q_h \rvert$
TD:JIT	Δ_t	ϕ	F	F	F	F	F	F	0	0	$\lvert Q_t \rvert$	0
HC:LJIT	ϕ	Δ_h	F	F	F	F	F	F	0	m	0	m
TD:LJIT	Δ_t	ϕ	F	F	F	F	F	F	m	0	m	0

A Simple Taxonomy Tree



Characterization of FAs Implementations

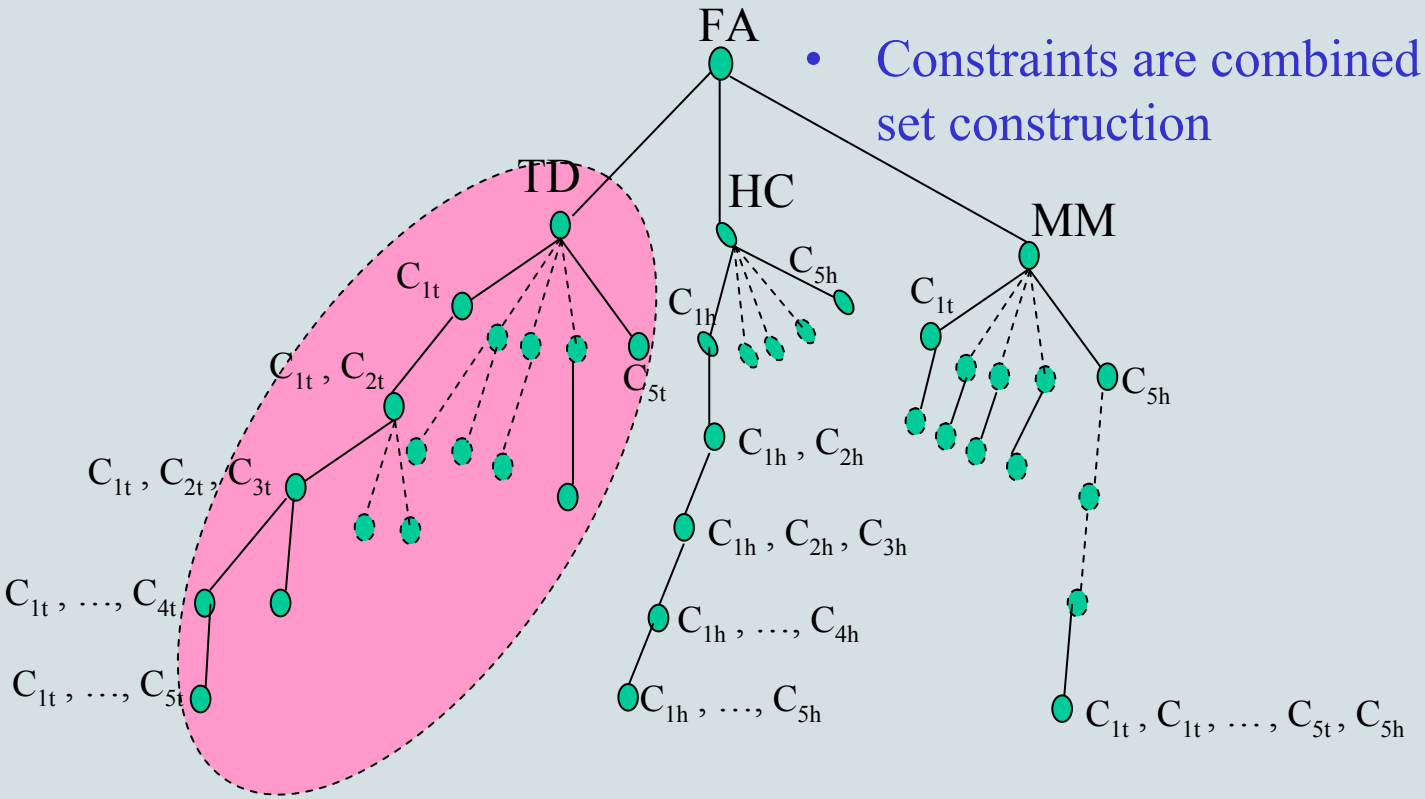
A Preliminary Taxonomy Tree



- Constraints are combined using power set construction

Characterization of FAs Implementations

A Preliminary Taxonomy Tree

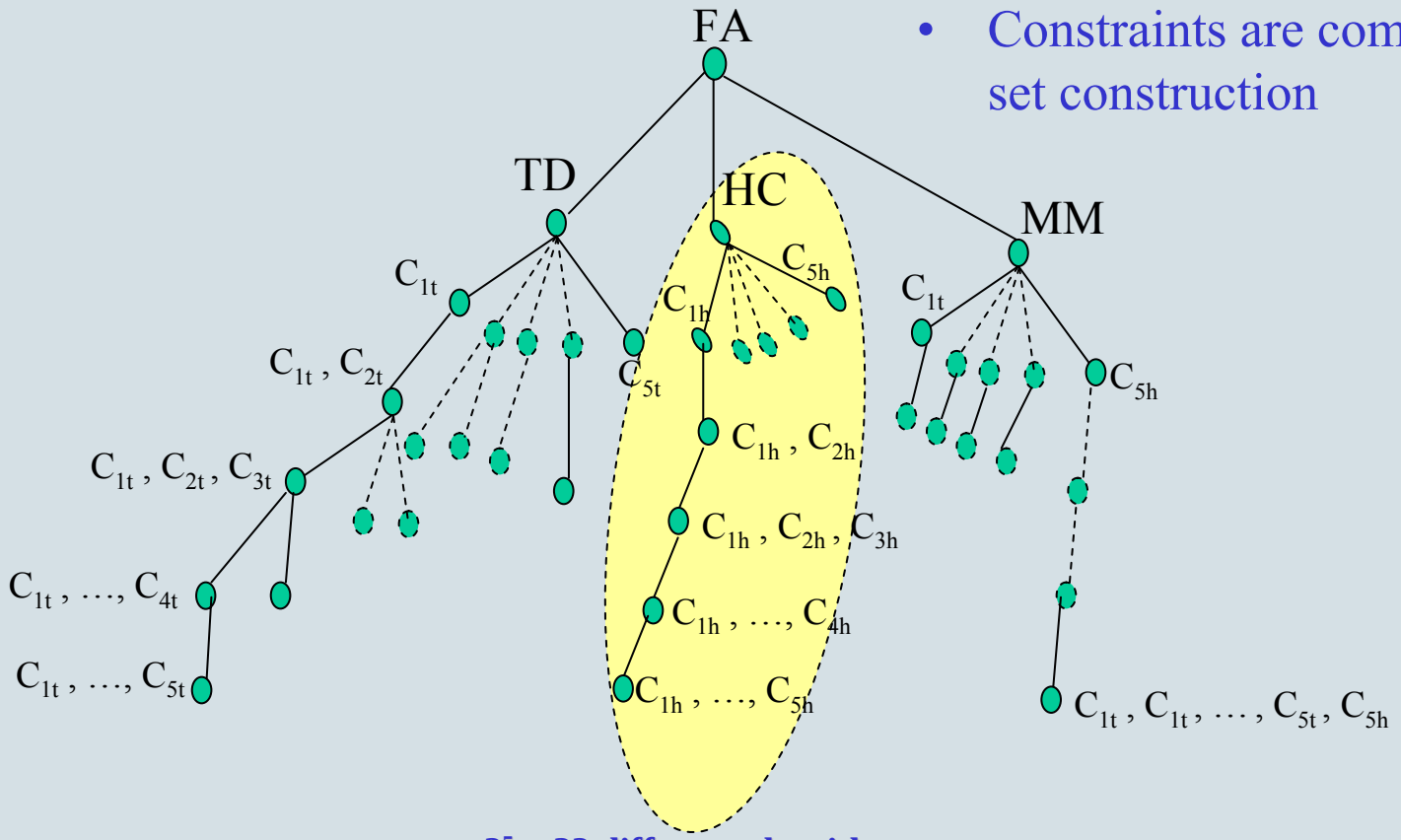


- Constraints are combined using power set construction

2^5 = 32 different algorithms

Characterization of FAs Implementations

A Preliminary Taxonomy Tree

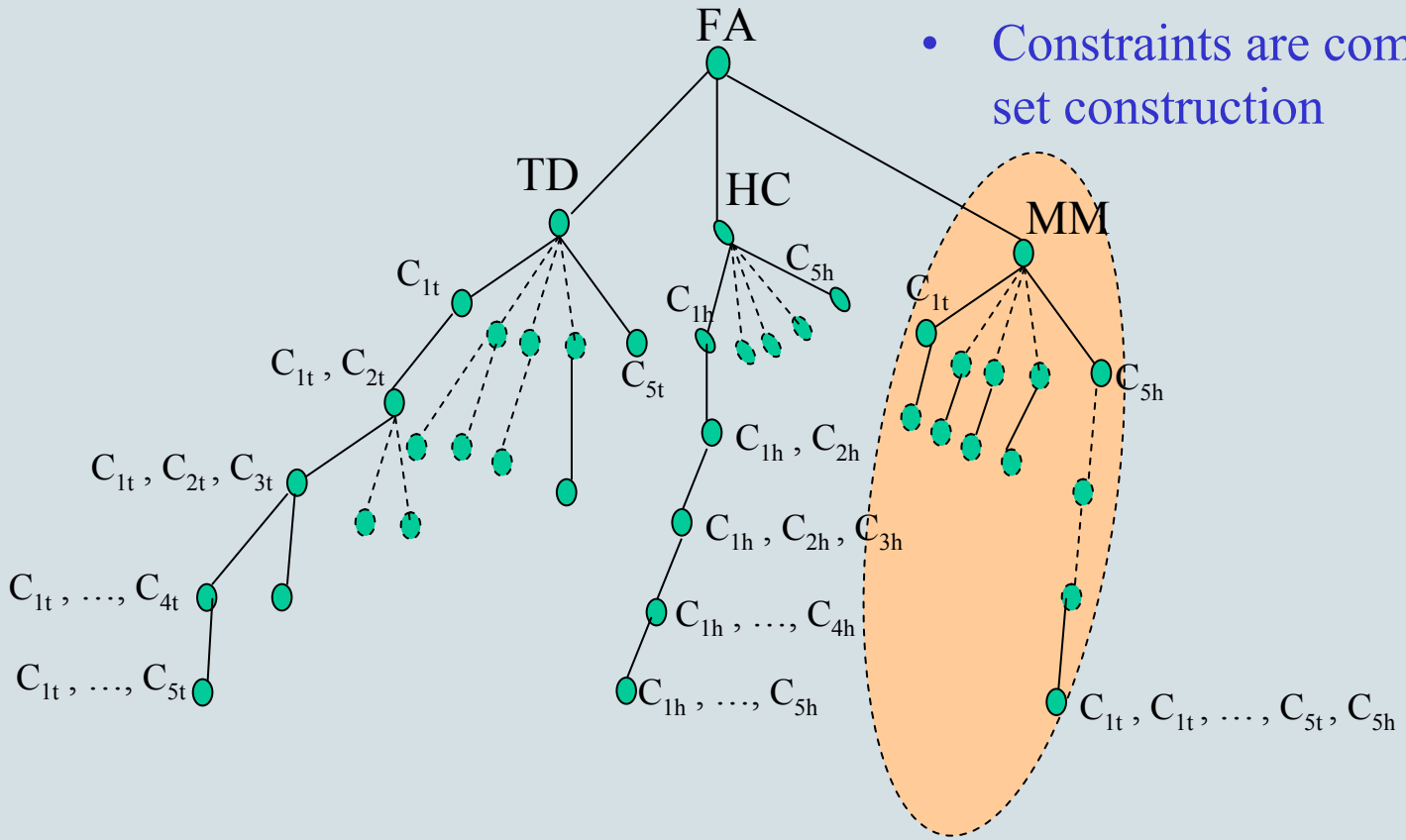


- Constraints are combined using power set construction

$2^5 = 32$ different algorithms

Characterization of FAs Implementations

A Preliminary Taxonomy Tree

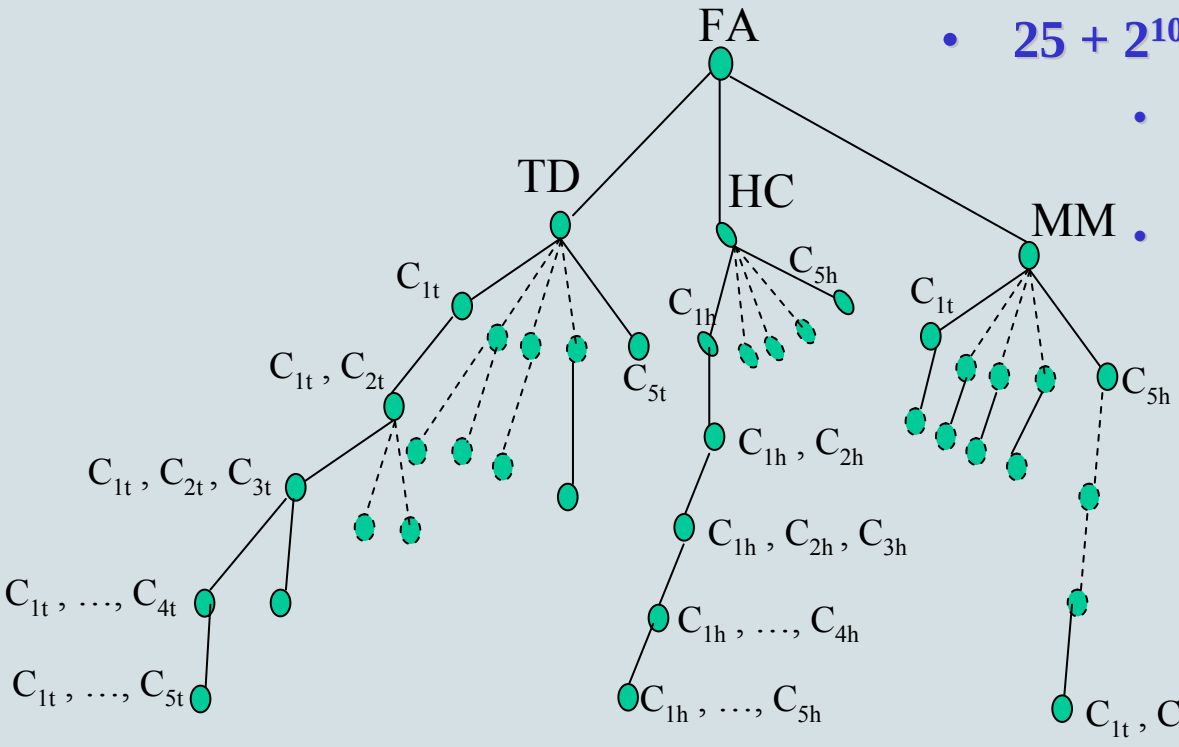


- Constraints are combined using power set construction

2^{10} = 1024 different algorithms

Characterization of FAs Implementations

A Preliminary Taxonomy Tree



- **$25 + 2^{10} = 1088$ different algorithms**
  - **Many can be removed according to practicality and redundancy**
  - **More can be added by assigning truth values to boolean constraints**

Future Work

- Performance Analysis of the kwk Algorithms
  - Cache miss correlation
    - Effects of cache structure
    - Effects of cache capacity
    - Effects of mapping/replacement algorithms
  - Effects of pipelining
  - Effects of branch prediction
- Hardware Design Recommendations
- Applications of kwk algorithms
  - DNA, NIDS, Virus Scanning…
- Hardware Implementations
- Toolkit & DSL for FIRE Station

Characterization of FAs Implementations

QUESTIONS?

In Search of a Suitable logo for FASTAR