Lexicalized Syntactic Analysis by Restarting Automata

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[2]The research was partially supported by the grant of the Czech Science Foundation No. 19-05704S during the author's stay at Institute of Computer Science, Czech Academy of Sciences.

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Lexicalized Syntactic Analysis

1. input sentence

PSC means an interesting conference

Lexicalized Syntactic Analysis

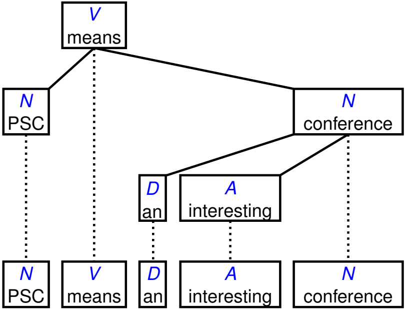
1. input sentence
2. lexicalization

N	*V*	*D*	*A*	*N*
PSC	means	an	interesting	conference

Lexicalized Syntactic Analysis

1. input sentence
2. lexicalization
3. lexicalized syntactic analysis – “Does the tagged word forms constitute a grammatically correct sentence which is correctly tagged?”

A Dependency tree
(dependency grammar)



Analysis by Reduction

The German team won the World Cup in Brazil.

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← each reduction

- preserves (non)correctness
- is local
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- checking correctness of sentences

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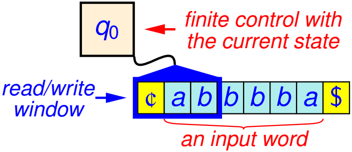
Analysis by reduction

- checking correctness of sentences
- localizing errors
- detecting (in)dependencies within a sentence

Restarting Automaton

RLWW-automaton



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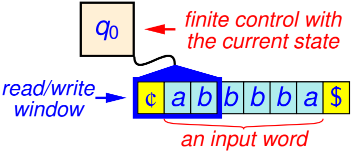

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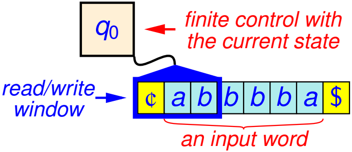

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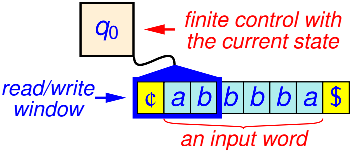

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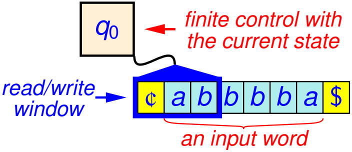

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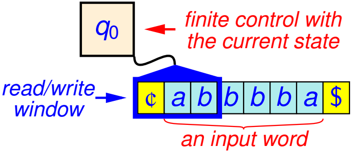

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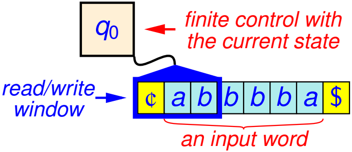

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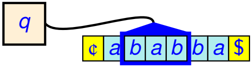
- a read/write *window* od length k
- a partial *transition function* δ

RLWW-Automaton

Possible Steps



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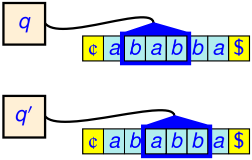

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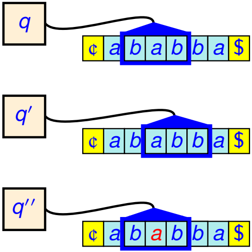

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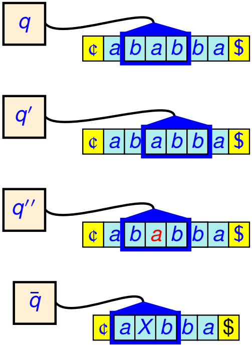

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  - must shorten the tape,
  - “complete” the window from the left
  - a new state is entered,

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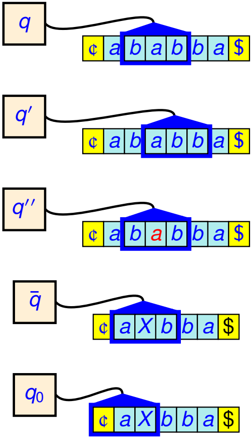

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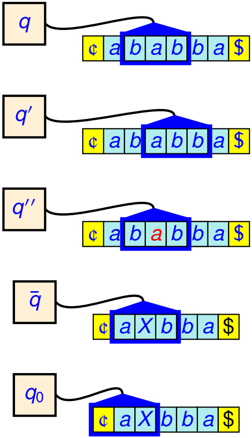

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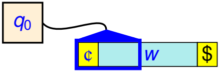

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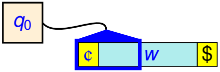

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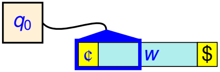

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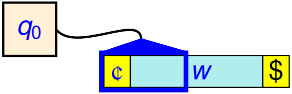
RLWW-Automaton

Cycles

- a restarting configuration:



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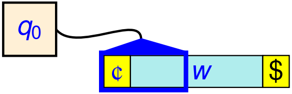

- a restarting configuration:
- a cycle – each part of a computation:

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  notation: $w \Rightarrow^c_{\mathcal{M}} w'$ if there is a cycle from restarting configuration with w on the tape and ending by the restart with w' on the tape

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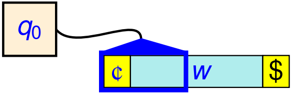

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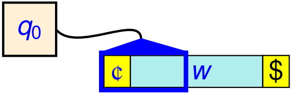

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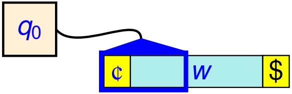

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- a computation: a sequence of cycles finished by a tail
- a RLWW(i)-automaton: can execute at most i rewrite instructions per cycle

h-Lexicalized RLWW(i)-automaton

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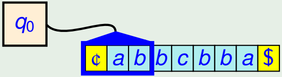
$$L_{\mathrm{A}}(\widehat{M}) = \{(h(w), w) \mid w \in L_{\mathrm{C}}(M)\}$$

- obviously $L(\widehat{M}) \subseteq L_{\mathrm{hP}}(\widehat{M}) = h(L_{\mathrm{C}}(\widehat{M}))$

RLWW-Automaton Accepting Palindromes with Marked Centers $L_{\mathrm{pal},c} = \{ wcw^R \mid w \in \{a,b\}^* \}$

Example 1



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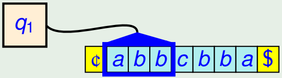

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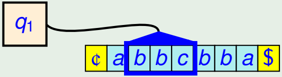

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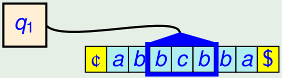

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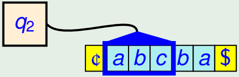

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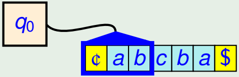

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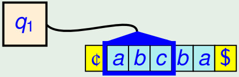

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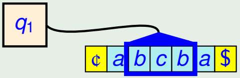

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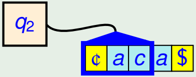

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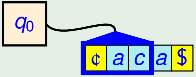

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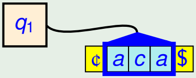

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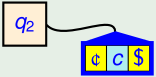

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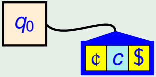

$L(M) = \{ wcw^R \mid w \in \{a,b\}^* \}$

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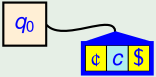

$$L(M) = \{ wcw^R \mid w \in \{a,b\}^* \}$$
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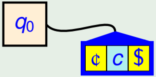

$L(M) = \{ wcw^R \mid w \in \{a, b\}^* \}$

$L_{\mathrm{C}}(M) = \{ wcw^R \mid w \in \{a, b\}^* \}$

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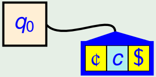

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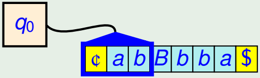
only contextual rewritings = deletes only, at most 2 factors in one rewrite step

RLWW-Automaton Accepting Even Palindromes $L_{\mathrm{pal}} = \{ww^R \mid w \in \{a,b\}^*\}$

Example 2

$$\begin{aligned}\Sigma &= \{a,b\},\\ \Gamma &= \{a,b,A,B\},\\ &\quad h(A) = a,\ h(B) = b,\end{aligned}$$



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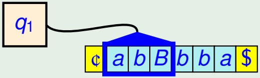

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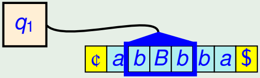

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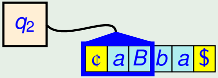

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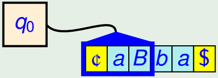

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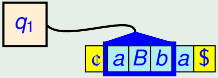

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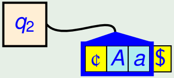

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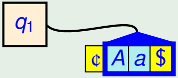

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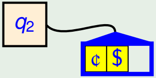

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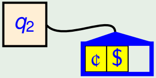

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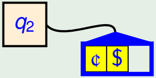

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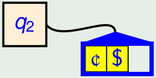

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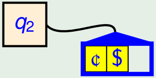

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- only contextual rewritings = deletes only, at most 2 factors in one rewrite step

The Power of RLWW(i)-automata

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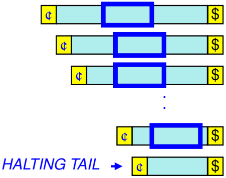

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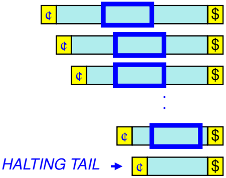

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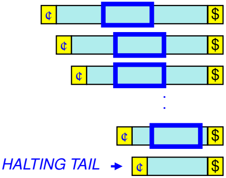
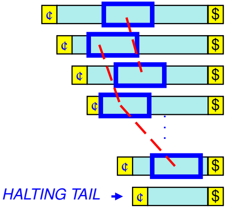


- a monotone automaton: all its computations are monotone
- $\mathcal{L}(\text{mon-RLWW}(1)) = \text{CFL}$

j-Monotone Automata

- a *j*-monotone computation: the places of rewriting can be partitioned into at most *j* (noncontiguous) monotone subsequences



- a *j*-monotone automaton: all its computations are *j*-monotone

Basic Correctness Preserving Property

- an hRLWW(i)-automaton is basically correctness preserving if $u \Rightarrow_M^{c^*} v$ and $u \in L_{\mathrm{C}}(M)$ induce that $v \in L_{\mathrm{C}}(M)$, and therewith $h(v) \in L_{\mathrm{hP}}(M)$ and $(h(v), v) \in L_{\mathrm{A}}(M)$
- **Fact:** each deterministic hRLWW(i)-automaton is basically correctness preserving.

Strong Cyclic Form

An hRLWW-automaton M is in strong cyclic form if it does not halt on any word of length greater than the size of its read/write window

Lemma 3

Each RLWW(i)*-automaton* M *can be transformed into* scf-RLWW(i)*-automaton* M_{scf} *such that*

- $L_{\mathrm{C}}(M) = L_{\mathrm{C}}(M_{\mathrm{scf}})$,
- $u \Rightarrow^{c^*}_{M} v$ *implies* $u \Rightarrow^{c^*}_{M_{\mathrm{scf}}} v$, *for all words* u, v,
- *all reductions of* M_{scf} *that are not possible for* M *are in contextual form – they do not rewrite, delete at most two factors,*
- *if* M *is deterministic and/or* j*-monotone, then* M_{scf} *is deterministic and/or* j*-monotone.*

Strong Cyclic Form

Context-Free Constructions

- LRR $=$ the class of left-to-right regular languages
- syn-RLWW(i) means j-mon-RLWW(i) where $j \leq i$

Theorem 4

Let $X \in \{\text{hRLWW}(1), \text{hRLWWD}(1), \text{hRLWWC}(1)\}$*. Then*

- LRR $= \mathcal{L}_{\mathrm{C}}$(scf-det-syn-$X$) *and*
- CFL $= \mathcal{L}_{\mathrm{hP}}$(scf-det-syn-$X$).

Sensitivity to the Size of Window

- Basic and h-proper languages of scf-hRLWW(i)-automata are sensitive to the size of their windows, to the number of deletions by a reduction, and to the degree of monotonicity.
- small finite witness languages

Lemma 5

For $k \geq 2$:

(a) $\{a^k\} \in \mathcal{L}_C(k\text{-scf-fin}(0)\text{-det-mon-RLWC})$.

- RLWC*-automata: no auxiliary (non-input) symbols, contextual instructions only*
- fin(0)*- at most* 0 *cycles in each accepting computation*
- k *is the length of window*

(b) $\{a^k\} \notin \mathcal{L}_C((k-1)\text{-scf-hRLWW}) \cup \mathcal{L}_{hP}((k-1)\text{-scf-hRLWW})$.

Sensitivity to the Number of Rewrites per Cycle

- witness languages of cardinality two

Lemma 6

Let $k, j \geq 1$, *let* $L_2(j,k) = \{a^{k\cdot(j+1)}, a^k\}$.

(a) $L_2(j,k) \in \mathcal{L}_{\mathrm{C}}(k\text{-scf-fin(1)-det-mon-RLWC}(j))$.

(b) $L_2(j,k) \notin \mathcal{L}_{\mathrm{C}}(k\text{-scf-hRLWW}(j')) \cup \mathcal{L}_{\mathrm{hP}}(k\text{-scf-hRLWW}(j'))$ *for any* $j' < j$.

Sensitivity to the Degree of Monotonicity

- finite witness languages

Lemma 7

Let $k, j \geq 2$. *There exist languages* $L_3(j,k) \subset \{a,b,c\}^*$ *of cardinality* $j^2 + j + 1$ *such that:*

(a) $L_3(j,k) \in \mathcal{L}_{\mathrm{C}}(k\text{-scf-fin}(j+j^2)\text{-det-mon}(j)\text{-RLWC}(j))$.

(b) $L_3(j,k) \notin \mathcal{L}_{\mathrm{C}}(k\text{-scf-mon}(j')\text{-hRLWW}(j)) \cup \mathcal{L}_{\mathrm{hP}}(k\text{-scf-mon}(j')\text{-hRLWW}(j))$ *for any* $j' < j$.

(c) $L_3(j,k) \notin \mathcal{L}_{\mathrm{C}}(k\text{-scf-hRLWW}(j')) \cup \mathcal{L}_{\mathrm{hP}}(k\text{-scf-hRLWW}(j'))$ *for any* $j' < j$.

Hierarchy of Contextually Transparent Language Classes

CTL(i) = the class of h-proper languages accepted by hRLWW(i)-automata that are

- deterministic, contextual, in the strong cyclic form
- synchronized – mon-(i)

CTLA(i) = the class of lexicalized analyses corresponding to CTL(i)

$$\begin{tikzcd}
\mathrm{CTL} \arrow[r] & \mathrm{CSL} \\
\vdots \arrow[u] & \\
\mathrm{CTL}(3) \arrow[u] & \\
\mathrm{CTL}(2) \arrow[u] & \\
\mathrm{CTL}(1) \arrow[u] \arrow[r, phantom, "="] & \mathrm{CFL} \arrow[uuuu]
\end{tikzcd}$$

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\end{tikzcd}$$

CTL $\subsetneq$ CSL

$\subseteq$: easy

$\subsetneq$: $L_{\mathrm{e}} = \{a^{2^n} \mid n \geq 0\} \notin$ CTL by contradiction

- if $a^{2^n} \in L_{\mathrm{hP}}(M)$ for some k-hRLWW(i)-automaton, then $a^{2^n} = h(w)$ for some $w \in L_{\mathrm{C}}(M)$ and there exists an accepting computation of M on w; the accepting computation contains at least one cycle
- the cycle starts by a reduction $w \Rightarrow_M w'$, where $|w| > |w'| \geq |w| - k \cdot i$ and $h(w') \in L_{\mathrm{hP}}(M)$
- for sufficiently large n, the length of $h(w')$ cannot be a power of 2 $\Rightarrow$ $h(w') \notin L_{\mathrm{hp}}(M)$ – a contradiction

A Refinement With Respect to the Window Size

h-Proper Language Classes

k-CTL(i) $=$ the class of h-proper languages accepted by hRLWW(i)-automata that are

- deterministic, contextual, in the strong cyclic form
- synchronized – mon-(i)
- of window size k

$$
\begin{tikzcd}
\text{1-CTL} \arrow[r] & \text{2-CTL} \arrow[r] & \text{3-CTL} \arrow[r] & \cdots \arrow[r] & \text{CTL} \arrow[r] & \text{CSL} \\
\vdots \arrow[u] & \vdots \arrow[u] & \vdots \arrow[u] & & \vdots \arrow[u] & \\
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\end{tikzcd}
$$

A Refinement With Respect to the Window Size

Lexicalized Analyses

k-CTLA(i) $=$ the class of lexicalized analyses by hRLWW(i)-automata that are

- deterministic, contextual, in the strong cyclic form
- synchronized – mon-(i)
- of window size k

$$
\begin{tikzcd}
1\text{-CTLA} \arrow[r] & 2\text{-CTLA} \arrow[r] & 3\text{-CTLA} \arrow[r] & \cdots \arrow[r] & \text{CTLA} \\
\vdots \arrow[u] & \vdots \arrow[u] & \vdots \arrow[u] & & \vdots \arrow[u] \\
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- **Conjecture:** The lexicalized syntactic analysis of full (four level) FGD can be described by tools very close to 24-CTLA(4).

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- In traditional and corpus linguistics, only finite language phenomena can be directly observed. The basic and h-proper languages of hRLWWC(i)-automata in strong cyclic form with constraints on the window size allow common classifications of finite phenomena as well as their infinite relaxations.
- Many practical problems in computational and corpus linguistic become decidable when we only consider languages parametrized by the size of the windows, or even easier when they are parametrized by a finite number of reductions.

Thank you for your attention!