Sensing Tree Automata as a Model of Syntactic Dependencies

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The Talk in One Minute

The research program

- a tight upper bound to the complexity of natural language dependencies?

In this talk

- Sensing tree automata as a uniform upper bound
- MG dependency trees

Spoilers

- A (linguistically) natural perspective!
- Empirically attested restrictions on movement
- Head-argument relations
- C-command and licensing conditions

Outline

Computational Theories of Language

The subregular program

Can we provide tight complexity characterizations for natural language?

- Particularly successful in phonology
  (Heinz et al. 2011; Chandlee 2014; Jardine 2016; McMullin 2016; Graf 2017; Graf and Mayer 2018)
- Some results for syntax
  - regular tree languages
    (Michaelis 2004; Kobele et al. 2007; Graf 2012)
  - subregular operations? (Graf 2012, 2018)
  - subregular dependencies? (Vu 2018; Vu et al. 2019)
  - subregular constraints? (Shafiei and Graf 2019)

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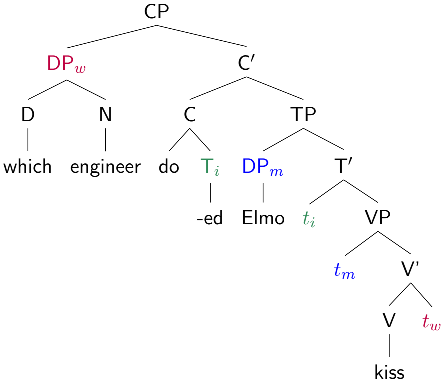
Can we gain a unified perspective for syntax?

Syntax?

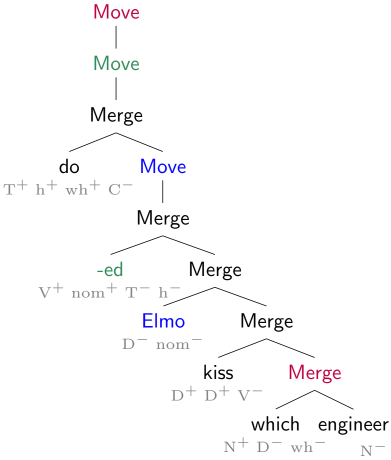
We need a formal model of syntactic structures.

- Minimalist grammars (MGs) are a formalization of Minimalist syntax. (Stabler 1997, 2011)
- Operations:
  - **Merge**
    category feature N^-, D^-, ...
    selector feature N^+, D^+, ...
  - **Move**
    licensee feature wh^-, nom^-, ...
    licensor feature wh^+, nom^+, ...
- Adopt Chomsky-Borer hypothesis:
  Grammar is just a finite list of feature-annotated lexical items
- The set of derivation trees is a regular tree language.
  (Michaelis 2004; Kobele et al. 2007; Graf 2012)

MG Syntax: Derivation Trees

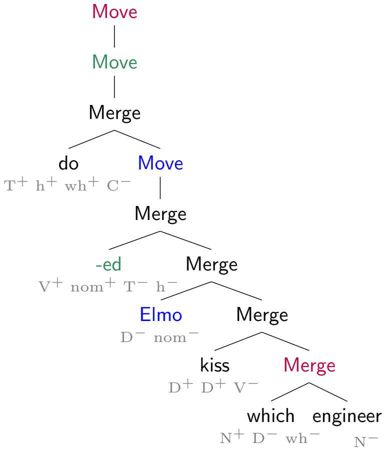


Phrase Structure Tree



Derivation Tree

MG Syntax: Dependency Trees



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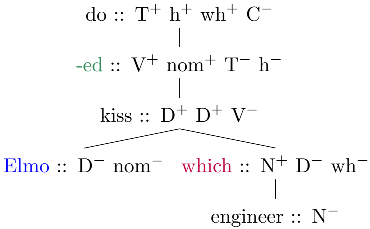


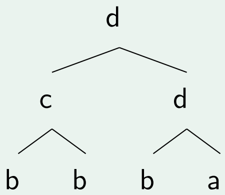
Dependency Tree

Sensing Tree Automata (STA)

Sensing Tree Automaton (Martens 2006)

Deterministic top-down tree automaton with finite look-ahead of 1.

Example: a *c-commanded* by c



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- $1(a) \rightarrow a$

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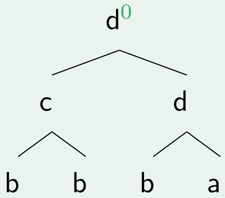

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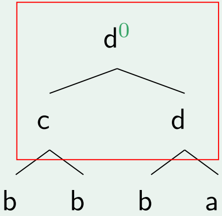

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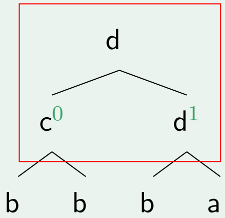

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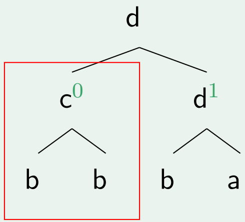

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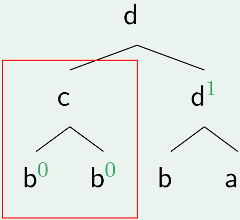

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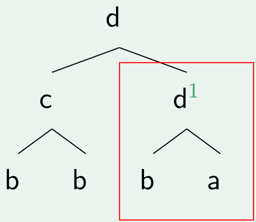

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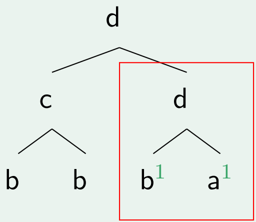

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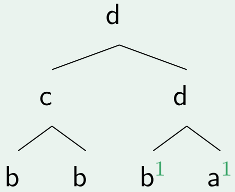

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Interim Summary

We are looking for a complexity upper bound for syntax...

- MG dependency trees (MDEP)
- STA

Upcoming

- MDEP[*merge*] $\subsetneq$ STA
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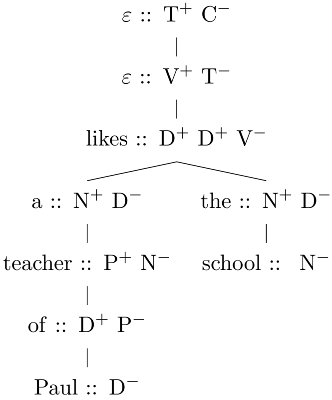
Dependency Trees, Merge, and Head-Argument Relations



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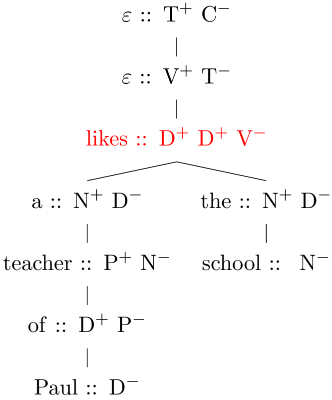

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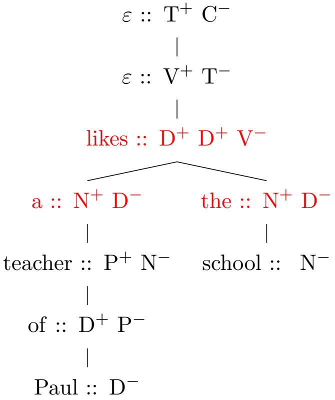

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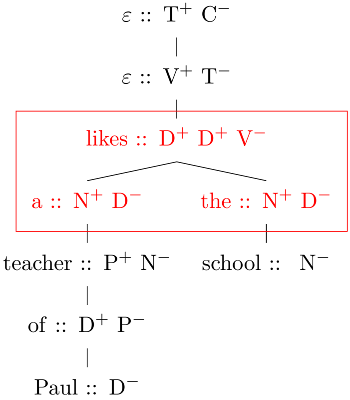

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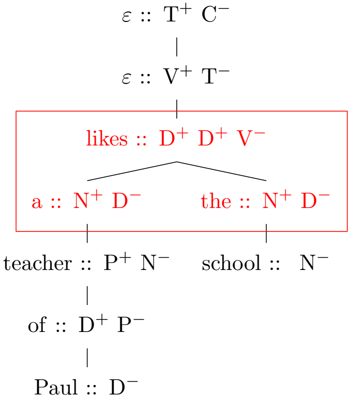

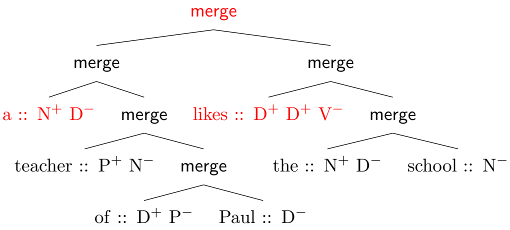

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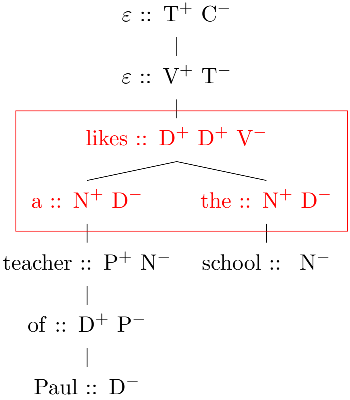

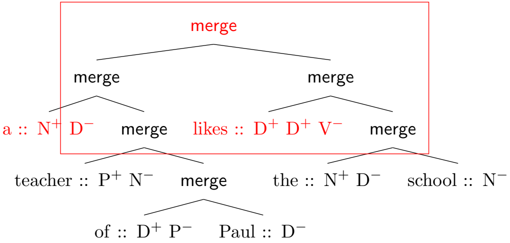

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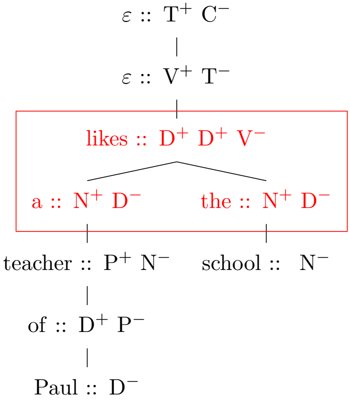
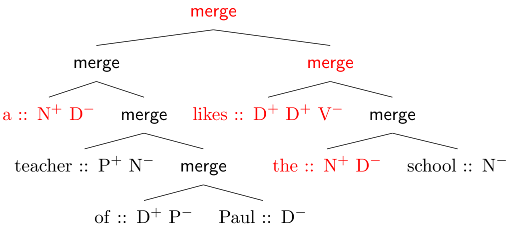
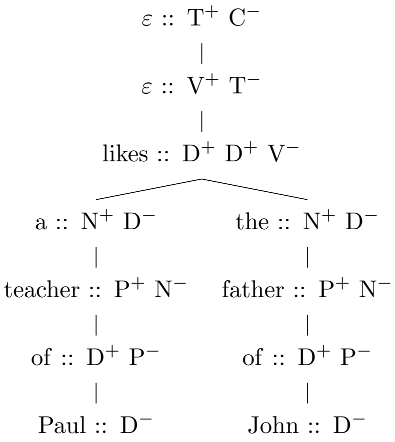




MDEP[merge] $\subsetneq$ STA



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    - $\text{likes} :: \mathrm{D}^{+}\ \mathrm{D}^{+}\ \mathrm{V}^{-}$
      - $\text{a} :: \mathrm{N}^{+}\ \mathrm{D}^{-}$
        - $\text{teacher} :: \mathrm{P}^{+}\ \mathrm{N}^{-}$
          - $\text{of} :: \mathrm{D}^{+}\ \mathrm{P}^{-}$
            - $\text{Paul} :: \mathrm{D}^{-}$
      - $\text{the} :: \mathrm{N}^{+}\ \mathrm{D}^{-}$
        - $\text{father} :: \mathrm{P}^{+}\ \mathrm{N}^{-}$
          - $\text{of} :: \mathrm{D}^{+}\ \mathrm{P}^{-}$
            - $\text{John} :: \mathrm{D}^{-}$

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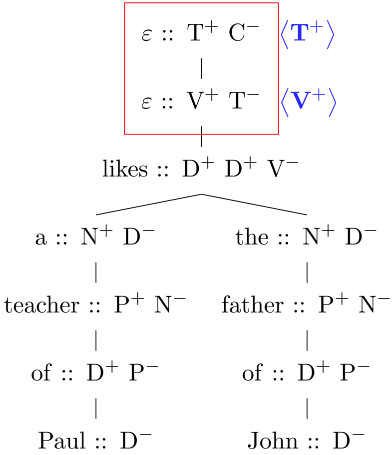

MDEP[merge] $\subsetneq$ STA

$\varepsilon :: T^+ \ C^- \quad \langle \mathbf{T^+} \rangle$

$\varepsilon :: V^+ \ T^- \quad \langle \mathbf{V^+} \rangle$

$\text{likes} :: D^+ \ D^+ \ V^- \quad \langle \mathbf{D^+ D^+} \rangle$

$\text{a} :: N^+ \ D^- \qquad \text{the} :: N^+ \ D^-$

$\text{teacher} :: P^+ \ N^- \qquad \text{father} :: P^+ \ N^-$

$\text{of} :: D^+ \ P^- \qquad \text{of} :: D^+ \ P^-$

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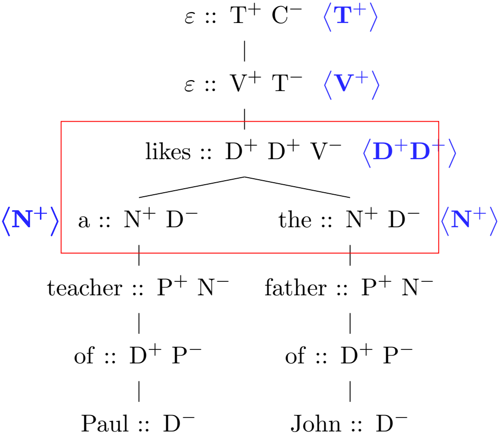

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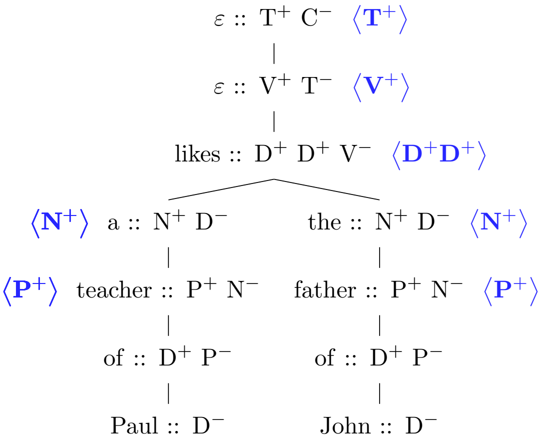

MDEP[merge] $\subsetneq$ STA

$\varepsilon :: \mathrm{T}^+\ \mathrm{C}^-\quad \langle \mathbf{T}^+ \rangle$

$\varepsilon :: \mathrm{V}^+\ \mathrm{T}^-\quad \langle \mathbf{V}^+ \rangle$

$\text{likes} :: \mathrm{D}^+\ \mathrm{D}^+\ \mathrm{V}^-\quad \langle \mathbf{D}^+\mathbf{D}^+ \rangle$

$\langle \mathbf{N}^+ \rangle\quad \text{a} :: \mathrm{N}^+\ \mathrm{D}^-$ $\qquad$ $\text{the} :: \mathrm{N}^+\ \mathrm{D}^-\quad \langle \mathbf{N}^+ \rangle$

$\langle \mathbf{P}^+ \rangle\quad \text{teacher} :: \mathrm{P}^+\ \mathrm{N}^-$ $\qquad$ $\text{father} :: \mathrm{P}^+\ \mathrm{N}^-\quad \langle \mathbf{P}^+ \rangle$

$\langle \mathbf{D}^+ \rangle\quad \text{of} :: \mathrm{D}^+\ \mathrm{P}^-$ $\qquad$ $\text{of} :: \mathrm{D}^+\ \mathrm{P}^-\quad \langle \mathbf{D}^+ \rangle$

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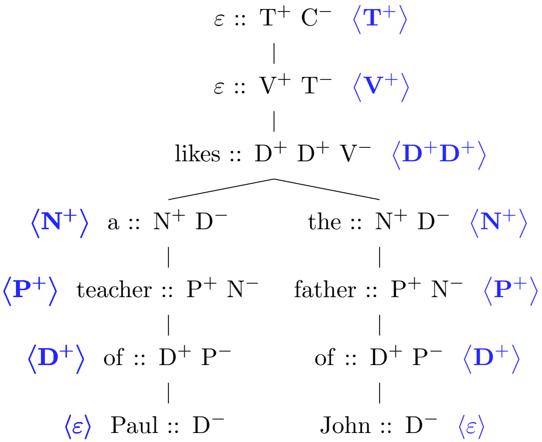
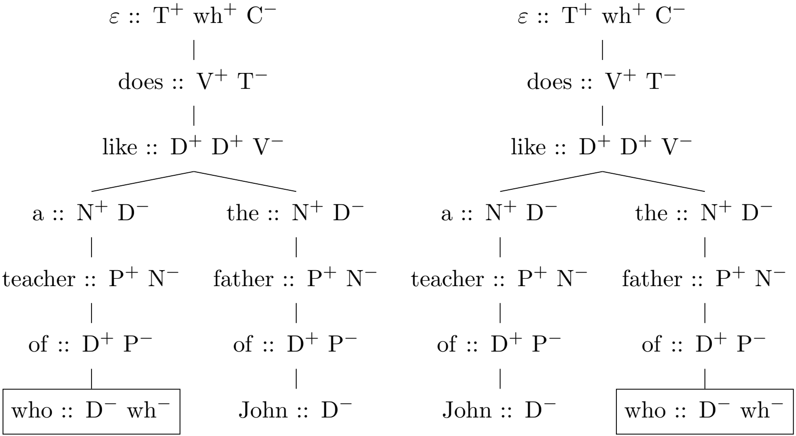


MDEP[merge,move]



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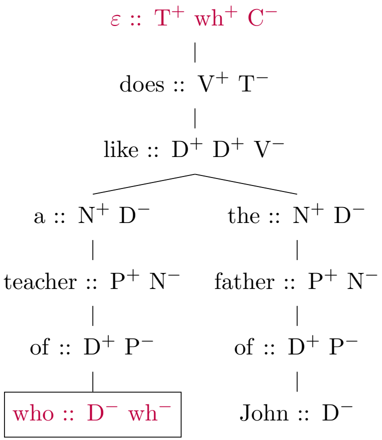

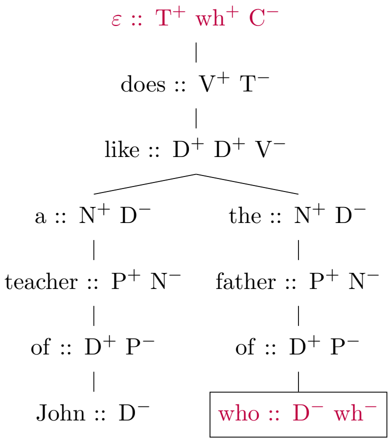

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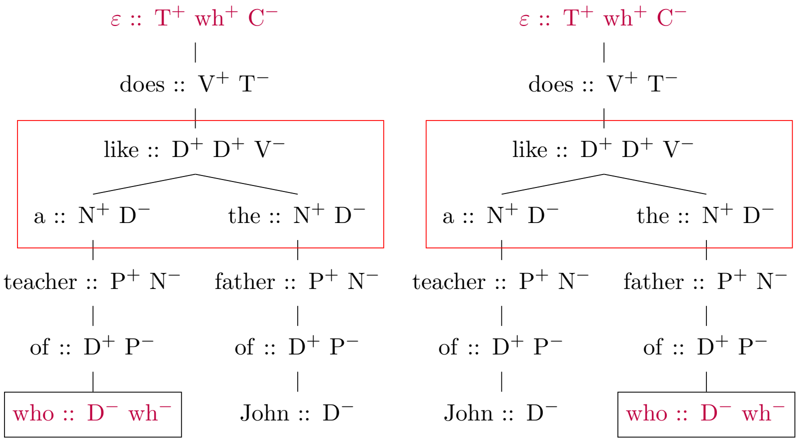

MDEP[merge,move] $\not\subseteq$ STA

Arbitrary movement leads to non-determinism for STAs.

- ε :: T^{+} wh^{+} C^{-}
  - ε :: V^{+} T^{-}
    - like :: D^{+} D^{+} V^{-}
      - a :: N^{+} D^{-}
        - teacher :: P^{+} N^{-}
          - of :: D^{+} P^{-}
            - John :: D^{-}
      - the :: N^{+} D^{-}
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          - of :: D^{+} P^{-}
            - who :: D^{-} wh^{-}

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            - John :: D^-
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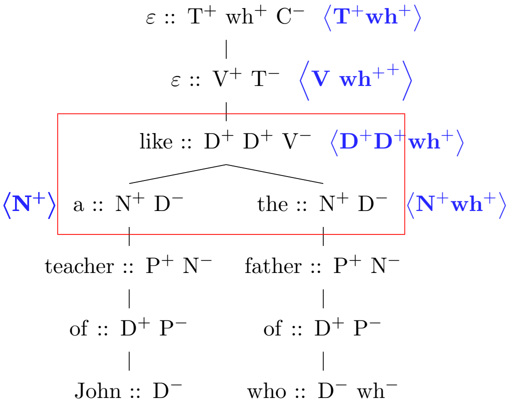

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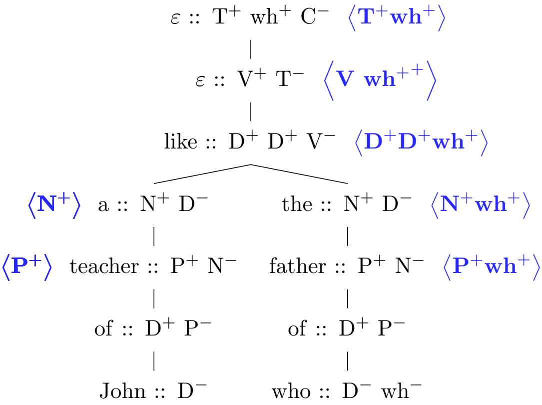

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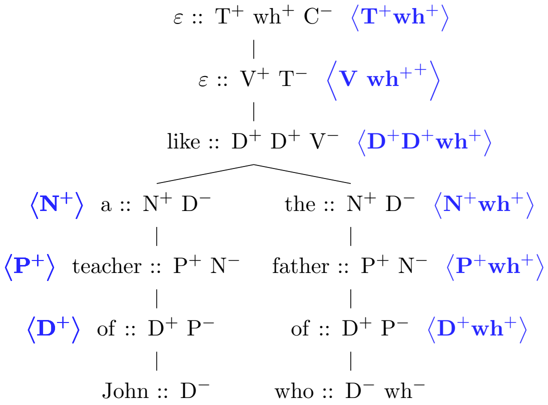

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$\varepsilon :: \mathrm{V}^{+}\ \mathrm{T}^{-}\quad \left\langle \mathbf{V\ wh^{+}}^{+} \right\rangle$

$\text{like} :: \mathrm{D}^{+}\ \mathrm{D}^{+}\ \mathrm{V}^{-}\quad \langle \mathbf{D^{+}D^{+}wh^{+}} \rangle$

$\langle \mathbf{N^{+}} \rangle\quad \text{a} :: \mathrm{N}^{+}\ \mathrm{D}^{-}$	$\text{the} :: \mathrm{N}^{+}\ \mathrm{D}^{-}\quad \langle \mathbf{N^{+}wh^{+}} \rangle$
$\langle \mathbf{P^{+}} \rangle\quad \text{teacher} :: \mathrm{P}^{+}\ \mathrm{N}^{-}$	$\text{father} :: \mathrm{P}^{+}\ \mathrm{N}^{-}\quad \langle \mathbf{P^{+}wh^{+}} \rangle$
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$\langle \varepsilon \rangle\quad \text{John} :: \mathrm{D}^{-}$	$\text{who} :: \mathrm{D}^{-}\ \mathrm{wh}^{-}\quad \langle \varepsilon \rangle$

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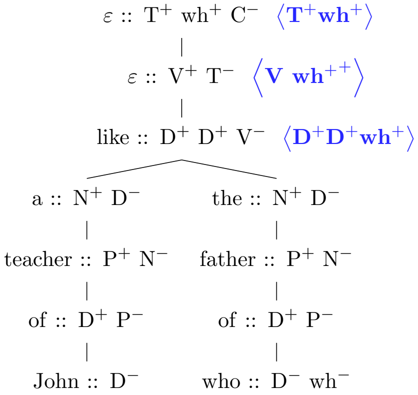

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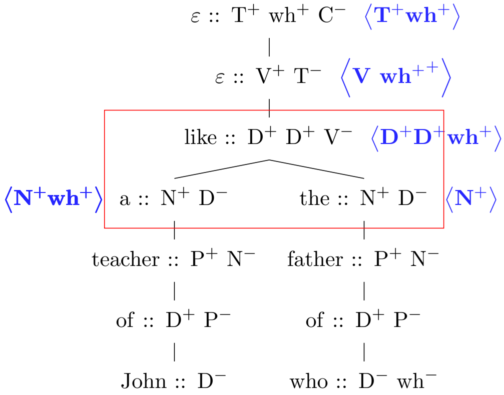

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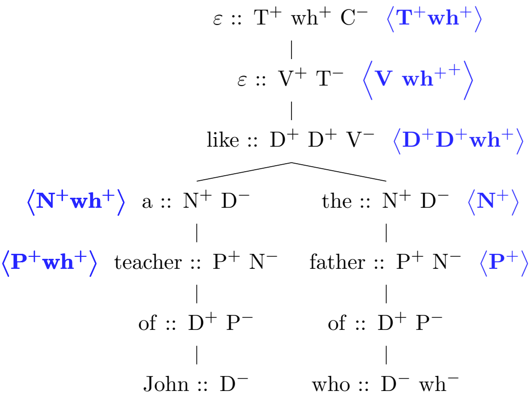

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Arbitrary movement leads to non-determinism for STAs.

$$\varepsilon :: \mathrm{T}^+\ \mathrm{wh}^+\ \mathrm{C}^- \quad \langle \mathbf{T}^+\mathbf{wh}^+ \rangle$$

$$\varepsilon :: \mathrm{V}^+\ \mathrm{T}^- \quad \left\langle \mathbf{V}\ \mathbf{wh}^{++} \right\rangle$$

$$\text{like} :: \mathrm{D}^+\ \mathrm{D}^+\ \mathrm{V}^- \quad \langle \mathbf{D}^+\mathbf{D}^+\mathbf{wh}^+ \rangle$$

$$\langle \mathbf{N}^+\mathbf{wh}^+ \rangle \quad \text{a} :: \mathrm{N}^+\ \mathrm{D}^- \qquad\qquad \text{the} :: \mathrm{N}^+\ \mathrm{D}^- \quad \langle \mathbf{N}^+ \rangle$$

$$\langle \mathbf{P}^+\mathbf{wh}^+ \rangle \quad \text{teacher} :: \mathrm{P}^+\ \mathrm{N}^- \qquad\qquad \text{father} :: \mathrm{P}^+\ \mathrm{N}^- \quad \langle \mathbf{P}^+ \rangle$$

$$\langle \mathbf{D}^+\mathbf{wh}^+ \rangle \quad \text{of} :: \mathrm{D}^+\ \mathrm{P}^- \qquad\qquad \text{of} :: \mathrm{D}^+\ \mathrm{P}^- \quad \langle \mathbf{D}^+ \rangle$$

$$\text{John} :: \mathrm{D}^- \qquad\qquad \text{who} :: \mathrm{D}^-\ \mathrm{wh}^-$$

MDEP[merge,move] $\not\subseteq$ STA

Arbitrary movement leads to non-determinism for STAs.

$\varepsilon :: \mathrm{T}^+\ \mathrm{wh}^+\ \mathrm{C}^- \quad \langle \mathbf{T^+wh^+} \rangle$

$\varepsilon :: \mathrm{V}^+\ \mathrm{T}^- \quad \langle \mathbf{V\ wh^{++}} \rangle$

$\text{like} :: \mathrm{D}^+\ \mathrm{D}^+\ \mathrm{V}^- \quad \langle \mathbf{D^+D^+wh^+} \rangle$

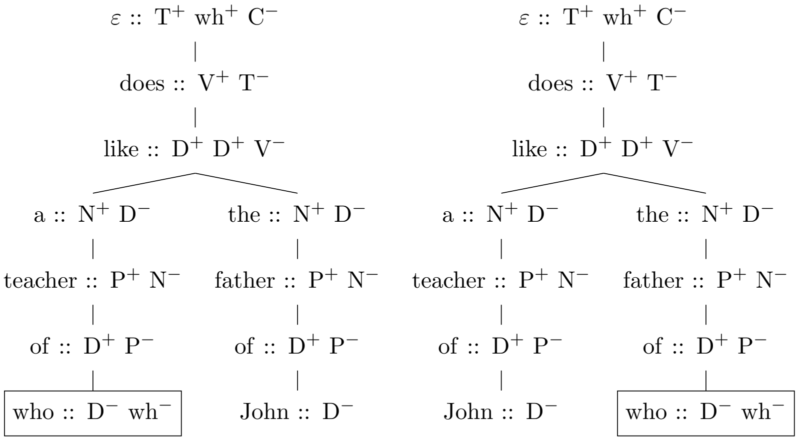
$\langle \mathbf{N^+wh^+} \rangle \quad \text{a} :: \mathrm{N}^+\ \mathrm{D}^- \qquad \text{the} :: \mathrm{N}^+\ \mathrm{D}^- \quad \langle \mathbf{N^+} \rangle$

$\langle \mathbf{P^+wh^+} \rangle \quad \text{teacher} :: \mathrm{P}^+\ \mathrm{N}^- \qquad \text{father} :: \mathrm{P}^+\ \mathrm{N}^- \quad \langle \mathbf{P^+} \rangle$

$\langle \mathbf{D^+wh^+} \rangle \quad \text{of} :: \mathrm{D}^+\ \mathrm{P}^- \qquad \text{of} :: \mathrm{D}^+\ \mathrm{P}^- \quad \langle \mathbf{D^+} \rangle$

$\langle \mathbf{wh^+} \rangle \quad \text{John} :: \mathrm{D}^- \qquad \text{who} :: \mathrm{D}^-\ \mathrm{wh}^- \quad \langle \mathbf{wh^-} \rangle$

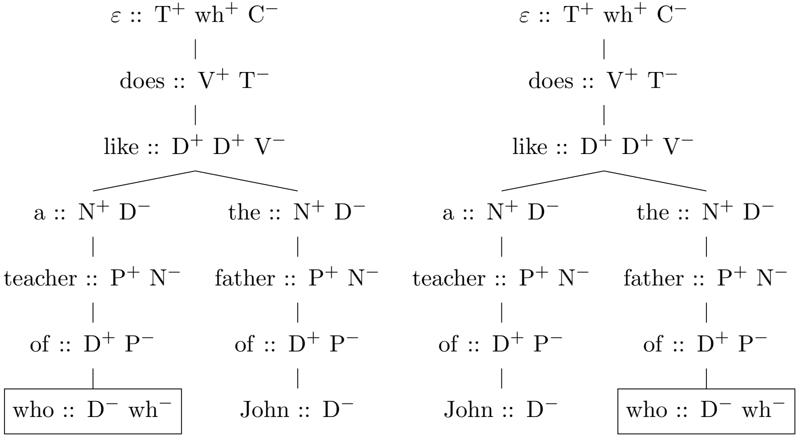
Restricting *move*



The Specifier Island Constraint (SpIC)

1. ***Who** does a teacher of __ like the father of John?

Restricting *move*

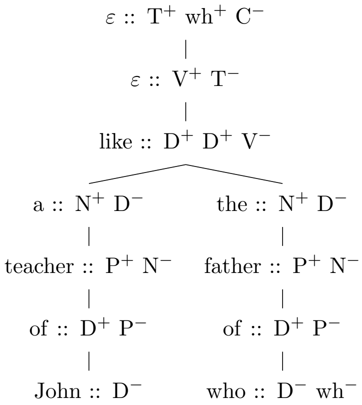


The Specifier Island Constraint (SpIC)

1. *__Who__ does a teacher of __ like the father of John?

MDEP[merge,move] + SpIC $\subsetneq$ STA

The SpIC guarantees STA recognition.



MDEP[merge,move] + SpIC $\subsetneq$ STA

The SpIC guarantees STA recognition.

- $\varepsilon :: \mathrm{T}^{+}\ \mathrm{wh}^{+}\ \mathrm{C}^{-}$ $\langle \mathbf{T^{+}wh^{+}} \rangle$
  - $\varepsilon :: \mathrm{V}^{+}\ \mathrm{T}^{-}$
    - like :: $\mathrm{D}^{+}\ \mathrm{D}^{+}\ \mathrm{V}^{-}$
      - a :: $\mathrm{N}^{+}\ \mathrm{D}^{-}$
        - teacher :: $\mathrm{P}^{+}\ \mathrm{N}^{-}$
          - of :: $\mathrm{D}^{+}\ \mathrm{P}^{-}$
            - John :: D^{-}
      - the :: $\mathrm{N}^{+}\ \mathrm{D}^{-}$
        - father :: $\mathrm{P}^{+}\ \mathrm{N}^{-}$
          - of :: $\mathrm{D}^{+}\ \mathrm{P}^{-}$
            - who :: $\mathrm{D}^{-}\ \mathrm{wh}^{-}$

MDEP[merge,move] + SpIC $\subsetneq$ STA

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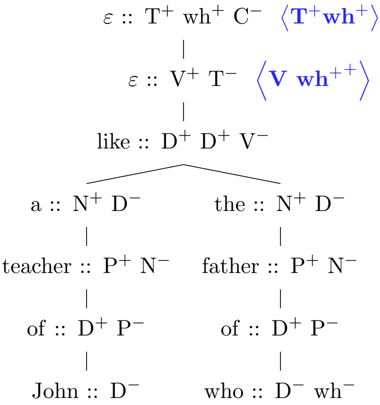

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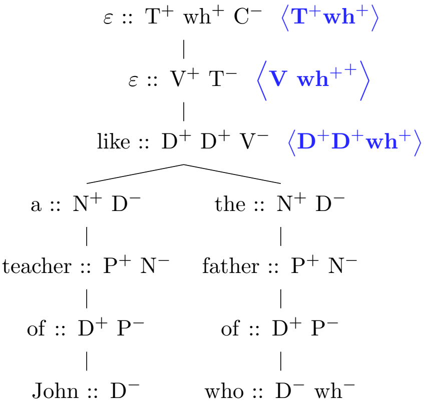

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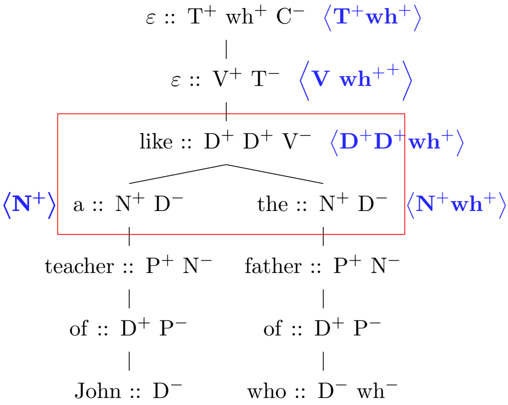

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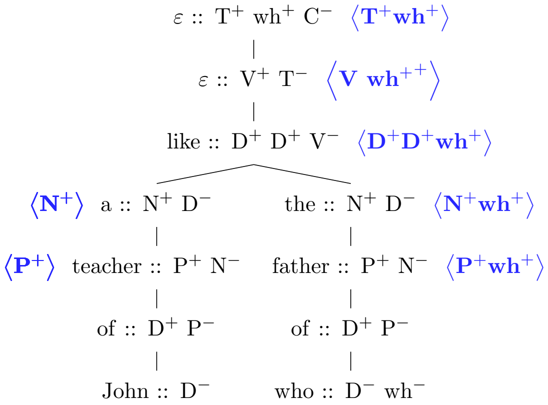

MDEP[merge,move] + SpIC $\subsetneq$ STA

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- $\varepsilon :: \mathrm{T}^{+}\ \mathrm{wh}^{+}\ \mathrm{C}^{-}$ $\langle \mathbf{T^{+}wh^{+}} \rangle$
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      - $\langle \mathbf{N^{+}} \rangle$ $\mathrm{a} :: \mathrm{N}^{+}\ \mathrm{D}^{-}$
        - $\langle \mathbf{P^{+}} \rangle$ $\mathrm{teacher} :: \mathrm{P}^{+}\ \mathrm{N}^{-}$
          - $\langle \mathbf{D^{+}} \rangle$ $\mathrm{of} :: \mathrm{D}^{+}\ \mathrm{P}^{-}$
            - $\mathrm{John} :: \mathrm{D}^{-}$
      - $\mathrm{the} :: \mathrm{N}^{+}\ \mathrm{D}^{-}$ $\langle \mathbf{N^{+}wh^{+}} \rangle$
        - $\mathrm{father} :: \mathrm{P}^{+}\ \mathrm{N}^{-}$ $\langle \mathbf{P^{+}wh^{+}} \rangle$
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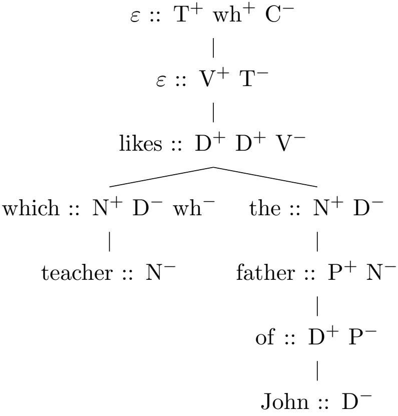
$$\text{like} :: \mathrm{D}^+\ \mathrm{D}^+\ \mathrm{V}^- \quad \langle \mathbf{D^+D^+wh^+} \rangle$$

$\langle \mathbf{N^+} \rangle$ a :: $\mathrm{N}^+\ \mathrm{D}^-$	the :: $\mathrm{N}^+\ \mathrm{D}^-$ $\langle \mathbf{N^+wh^+} \rangle$
$\langle \mathbf{P^+} \rangle$ teacher :: $\mathrm{P}^+\ \mathrm{N}^-$	father :: $\mathrm{P}^+\ \mathrm{N}^-$ $\langle \mathbf{P^+wh^+} \rangle$
$\langle \mathbf{D^+} \rangle$ of :: $\mathrm{D}^+\ \mathrm{P}^-$	of :: $\mathrm{D}^+\ \mathrm{P}^-$ $\langle \mathbf{D^+wh^+} \rangle$
$\langle \varepsilon \rangle$ John :: D^-	who :: $\mathrm{D}^-\ \mathrm{wh}^-$ $\langle \varepsilon \rangle$

Restricting *move* [cont.]

Movement of a specifier is still ok.



Restricting *move* [cont.]

Movement **of** a specifier is still ok.

- ε :: $T^+ \; wh^+ \; C^-$ $\langle \mathbf{T^+ wh^+} \rangle$
  - ε :: $V^+ \; T^-$ $\left\langle \mathbf{V \; wh^{++}} \right\rangle$
    - likes :: $D^+ \; D^+ \; V^-$ $\langle \mathbf{D^+ D^+ wh^+} \rangle$
      - which :: $N^+ \; D^- \; wh^-$
        - teacher :: N^-
      - the :: $N^+ \; D^-$
        - father :: $P^+ \; N^-$
          - of :: $D^+ \; P^-$
            - John :: D^-

Restricting *move* [cont.]

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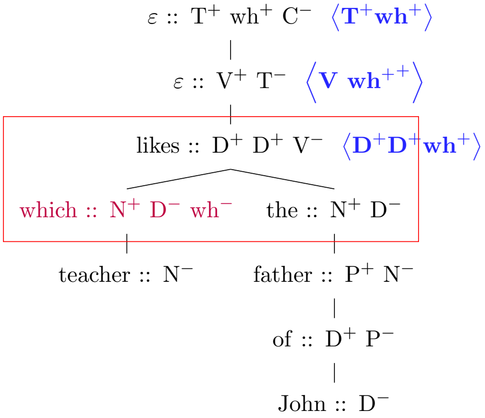

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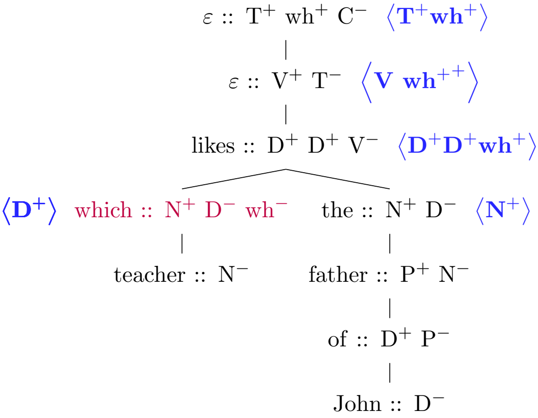

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$\text{of} :: \mathrm{D}^+ \ \mathrm{P}^- \quad \langle \mathbf{D}^+ \rangle$

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Restricting *move* [cont.]

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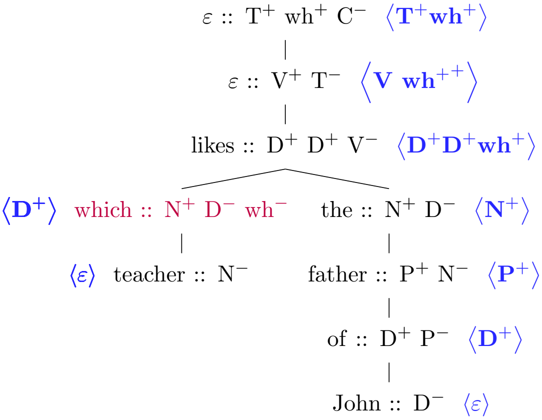

Interim Summary [2]

We are looking for a complexity upper bound for syntax...

The road so far

- MDEP[merge] $\subsetneq$ STA
- MDEP[merge,move] $\not\subseteq$ STA
- **But** MDEP[merge,move] $\subsetneq$ STA if we restrict move
  Movement constraints follow naturally: SpIC, CSC, ...

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Syntax is not just about Merge and Move...

NPI licensing

1a) *Every student said that the train **ever** arrives on time.
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Principle A

2a) *John said that **Mary** likes **himself**.
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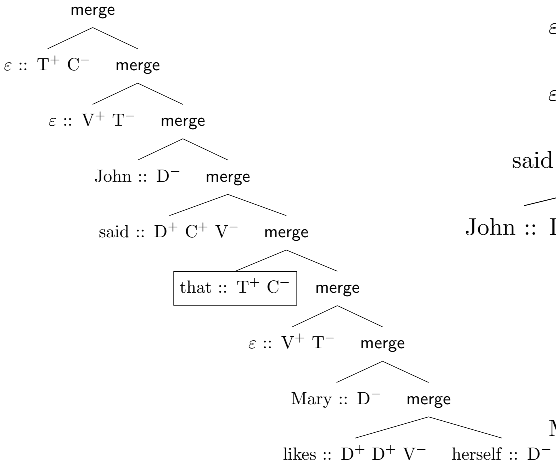
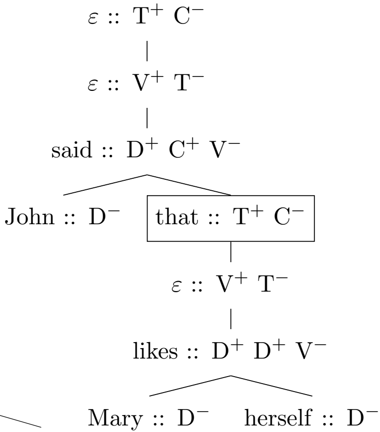
Dependency Trees and C-Command





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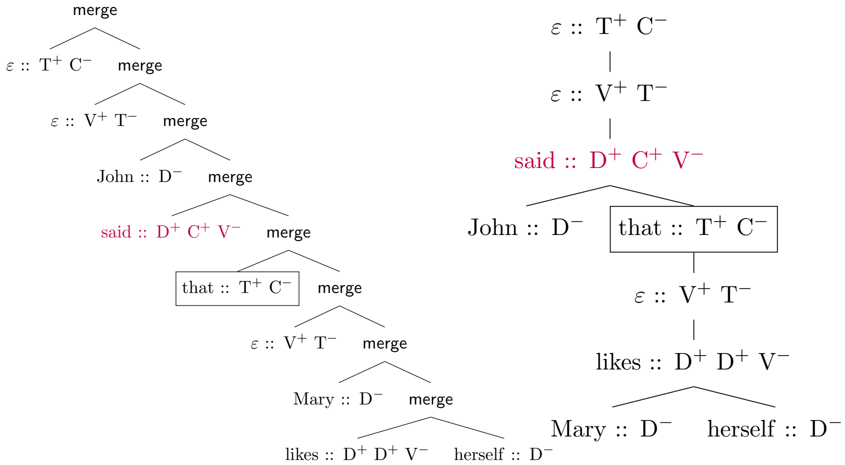

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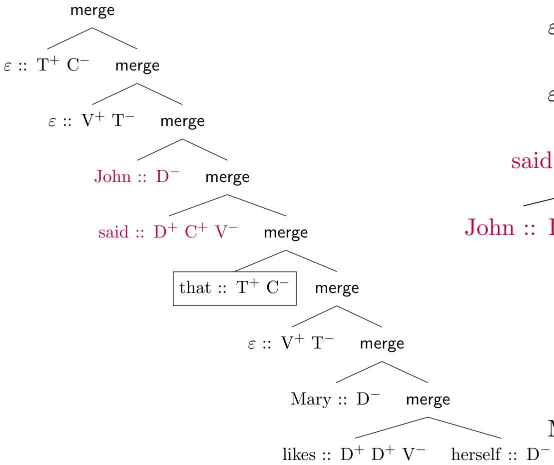

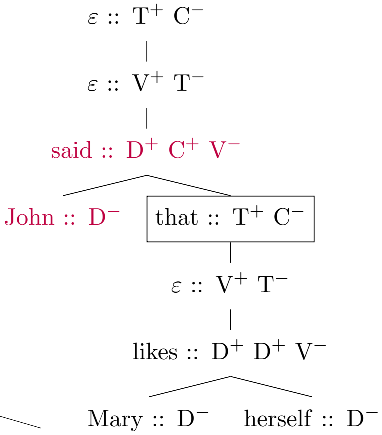

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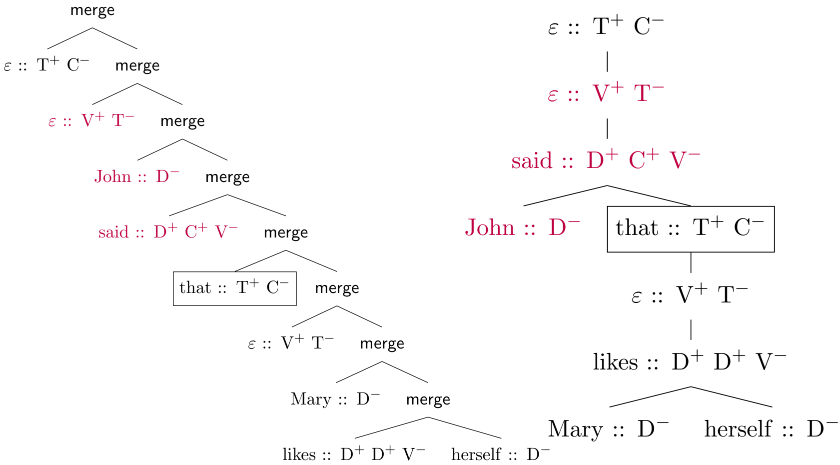

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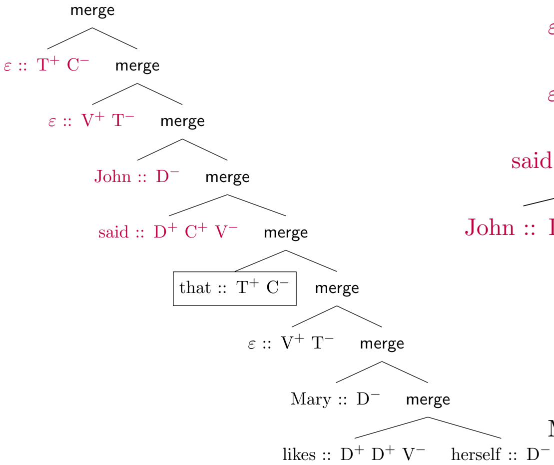
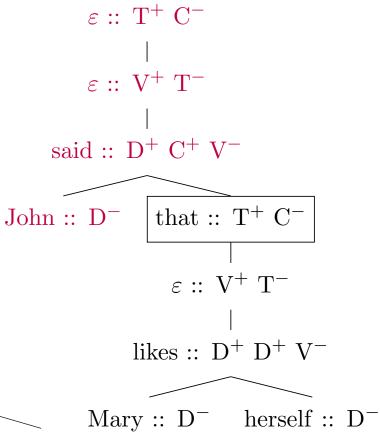
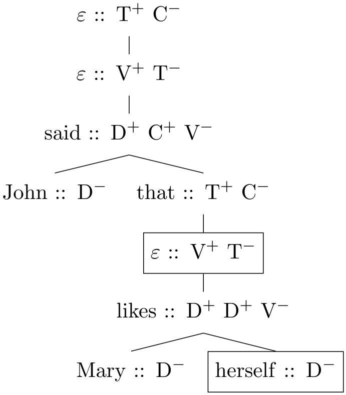




Enforcing Principle A with an STA

Principle A

Reflexives must be bound within their binding domain (e.g. TP).



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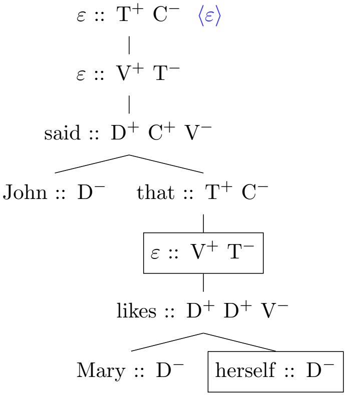

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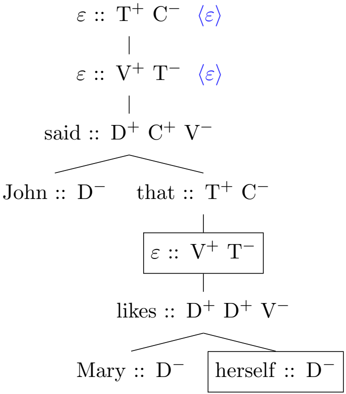

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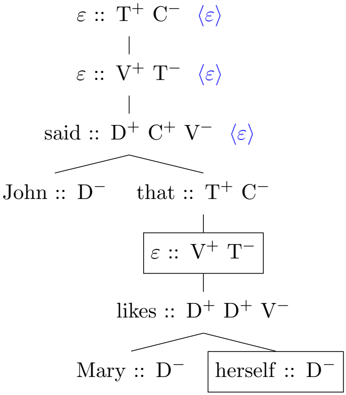

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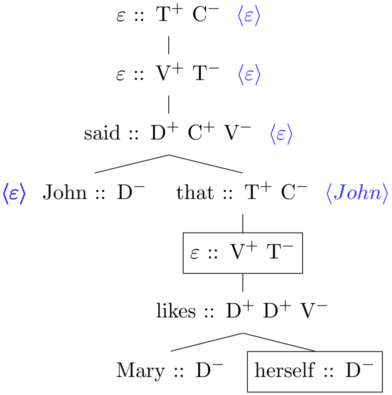

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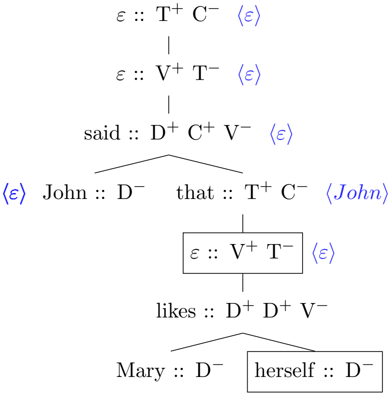

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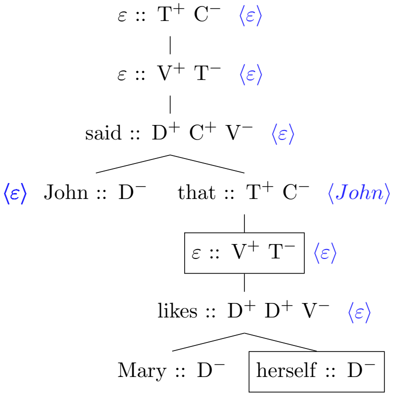

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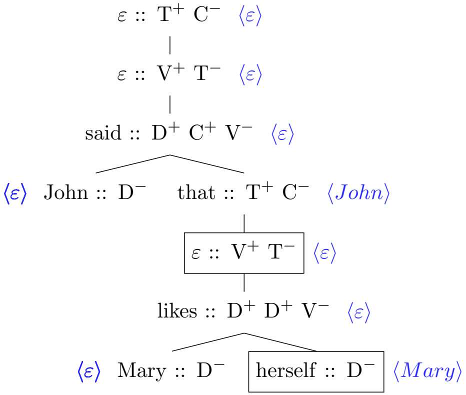

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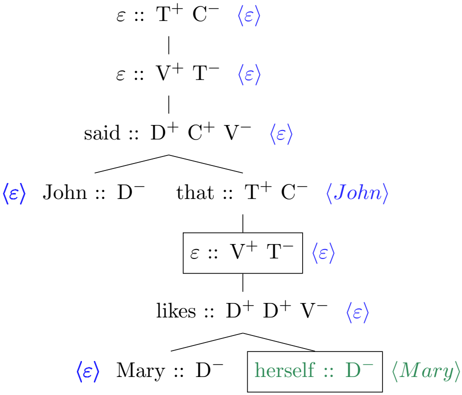

Example: Enforcing Principle A [cont.]

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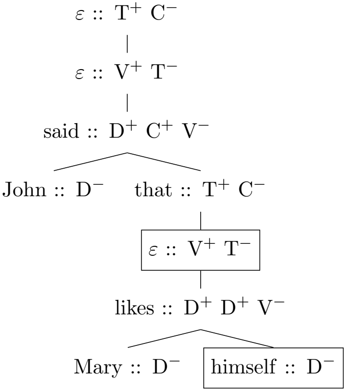

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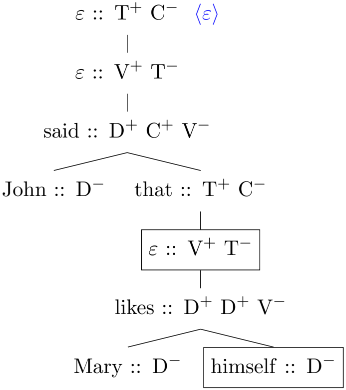

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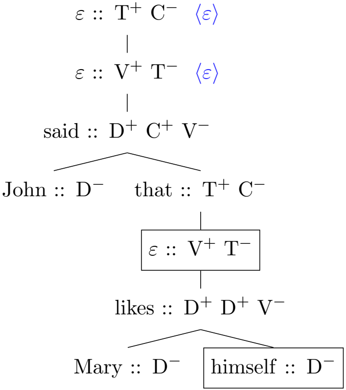

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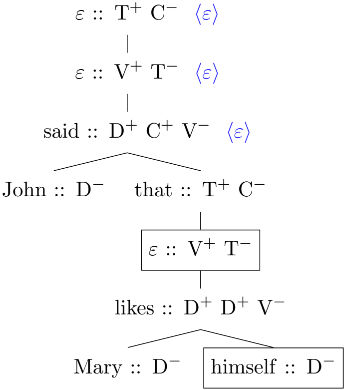

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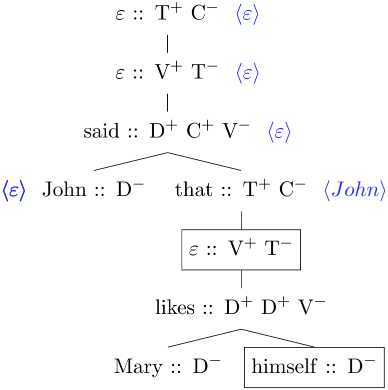

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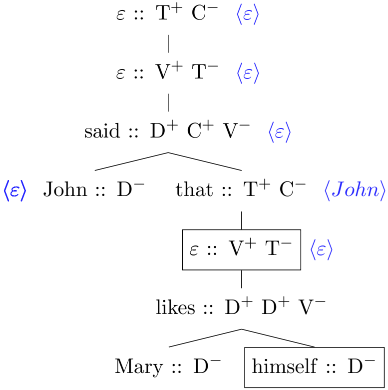

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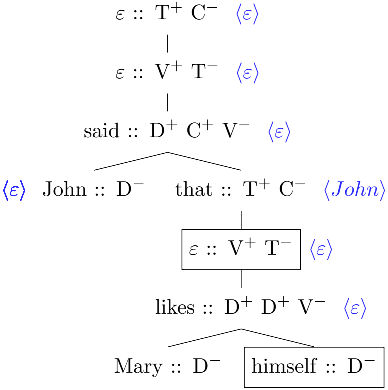

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Principle A

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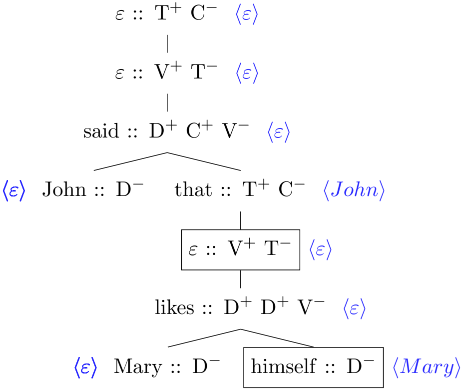

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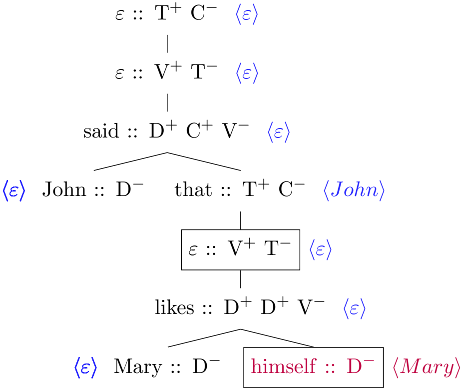

Conclusion

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- STA and C-Command Conditions

Merge, Move, Licensing enforced by the same machinery!

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STA as a uniform upper bound. But:

- Too permissive: Enforce arbitrary regular constraints
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- Subcommand
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- MG derivation trees?
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$\langle Thank\ you! \rangle$

Acknowledgments I

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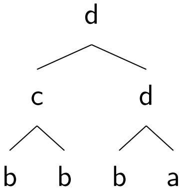
The Spine of a Node

- Example: spine(a)



STAs and spine closure (Martens 2006)

A regular tree language L belongs to the class STA iff L is spine closed.

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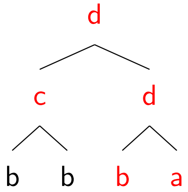

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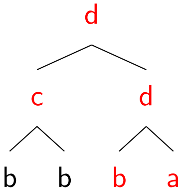

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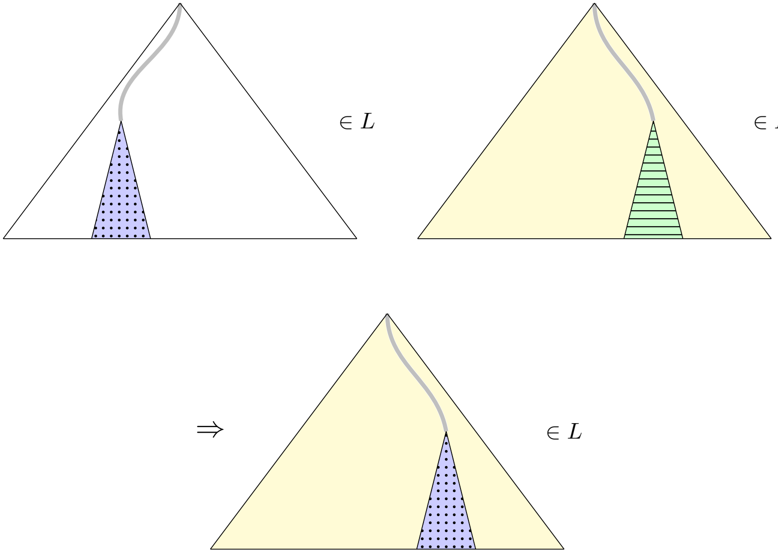
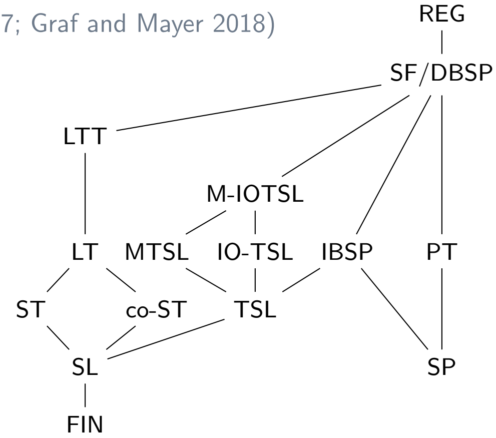


Subregular Complexity in Phonology

- **Subregular** phonology has proved to be a fruitful enterprise (Heinz et al. 2011; Chandlee 2014; Jardine 2016; McMullin 2016; Graf 2017; Graf and Mayer 2018)



C-Strings and Spines

Graf and Shafiei (2019)

C-command conditions as subregular **c-string** constraints.

Observation

spine(u) $\approx$ c-string(u)

Theorem

Every regular c-string constraint can be enforced by an STA.

c-string(the :: N^+ D^-) := ε :: T^+ wh^+ C^- $\uparrow$ does :: V^+ T^- $\uparrow$ like :: D^+ D^+ V^- $\uparrow$ a :: N^+ D^- the :: N^+ D^-

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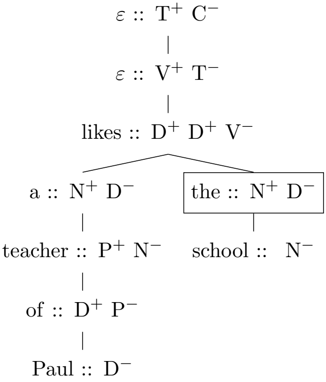

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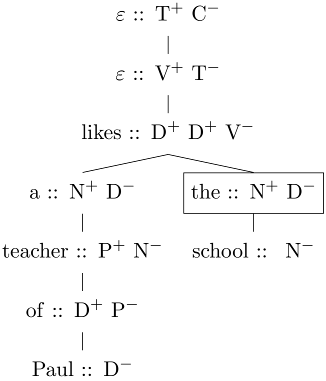

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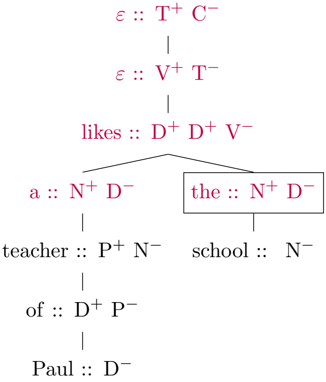

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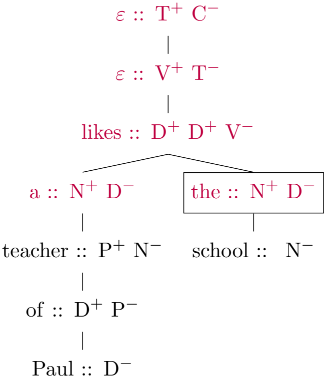

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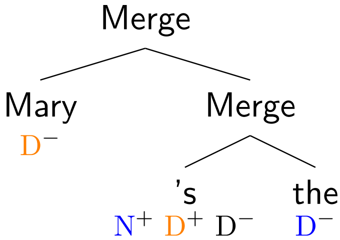
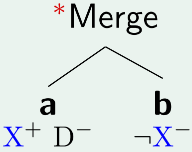


SL constraints on Merge

- We lift constraints from string n-grams to tree n-grams
- We get SL constraints over subtrees.



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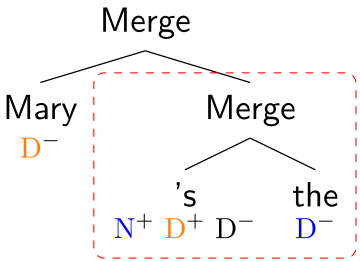

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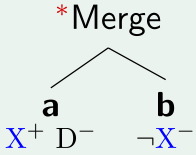
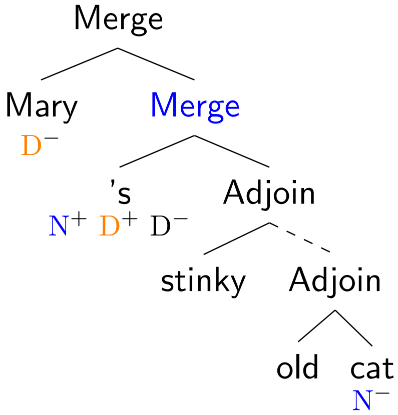


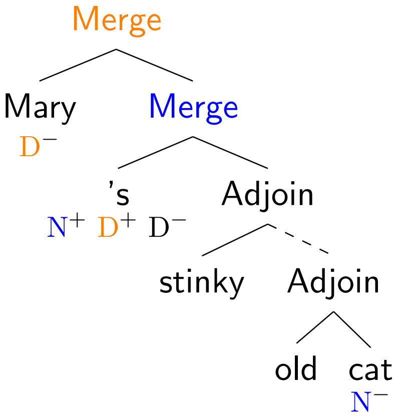
Non-Local Dependencies in Syntax

Let's stick to core operations:

- Move
- **Merge**: Unbounded adjunction ??



TSL over Trees: Projecting Tiers



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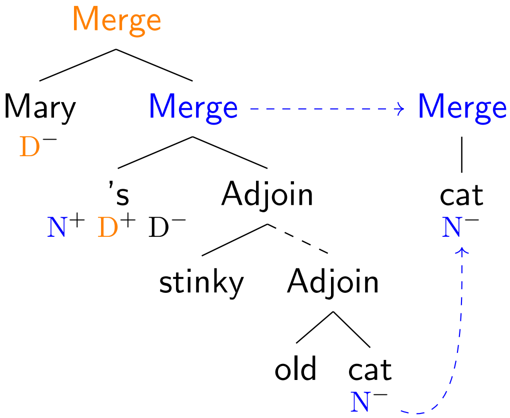

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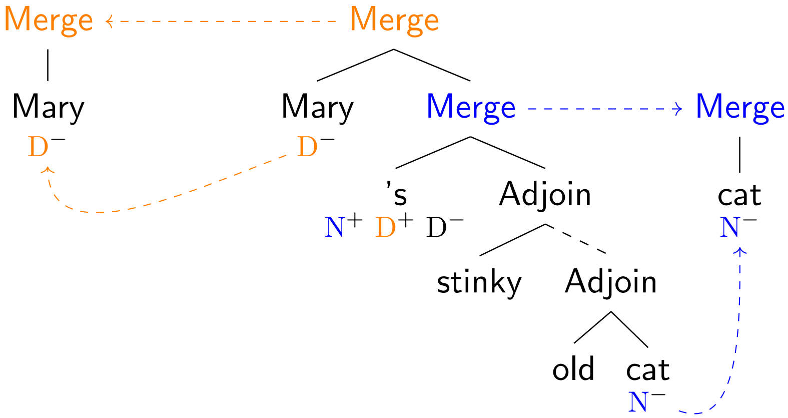

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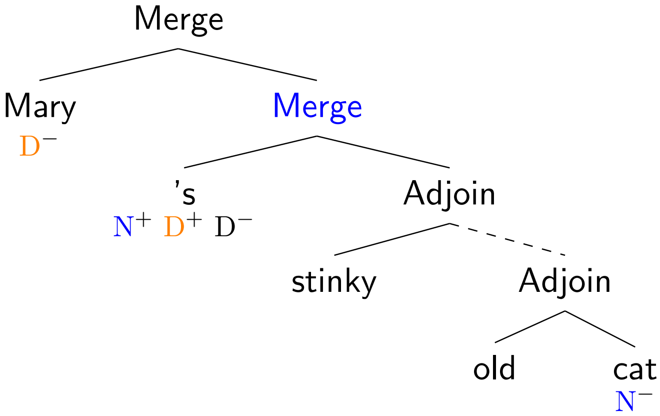

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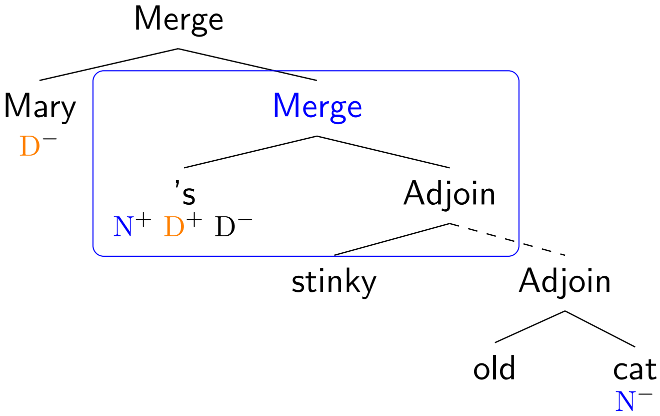

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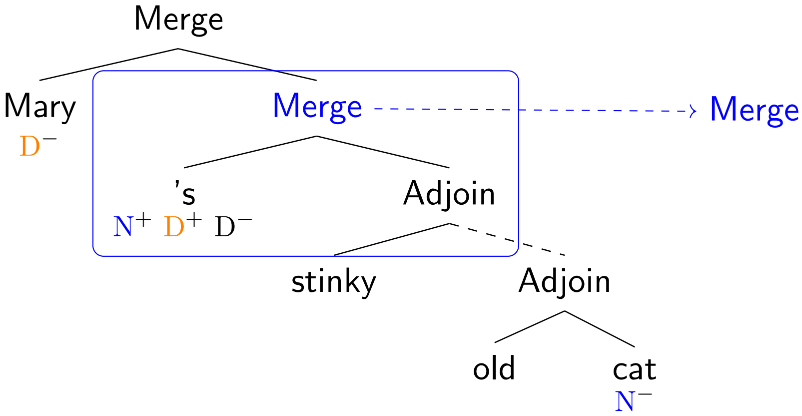

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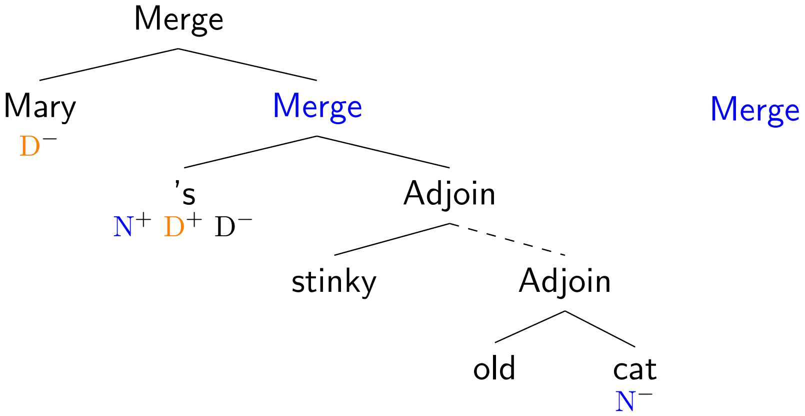

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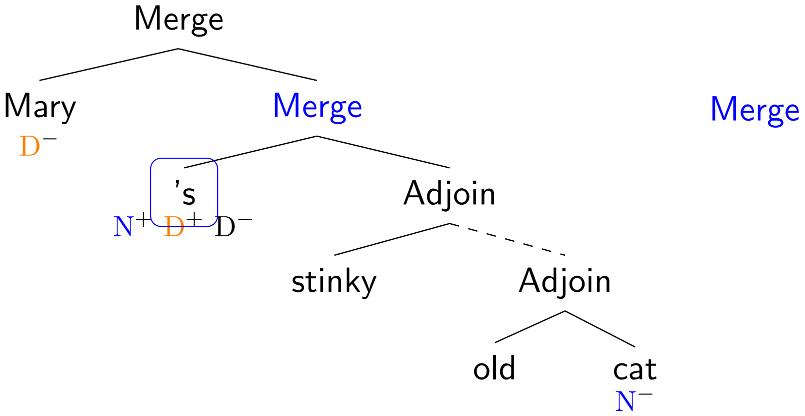

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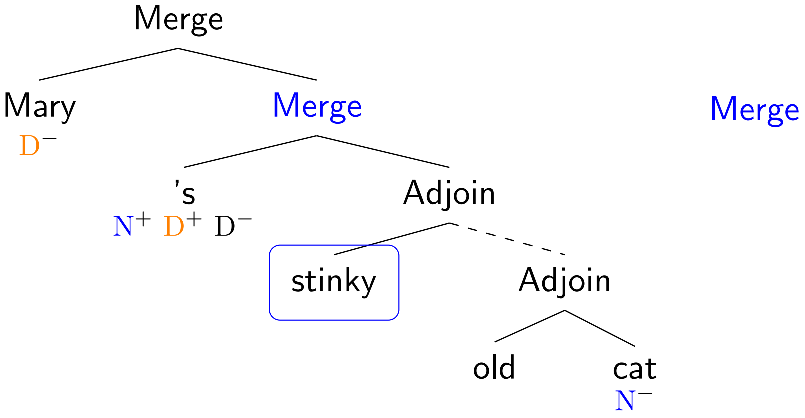

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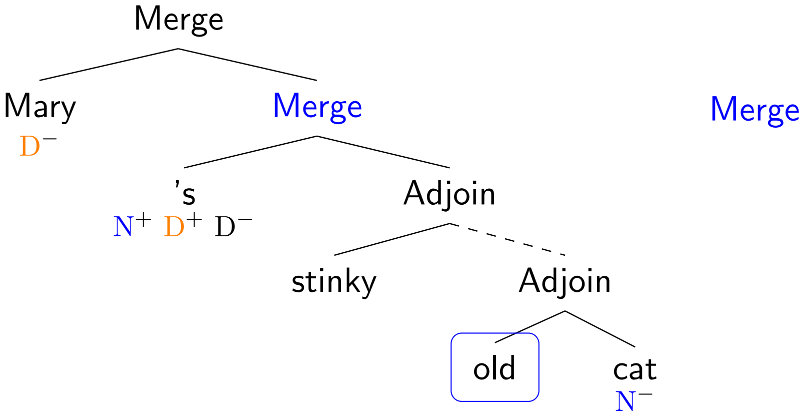

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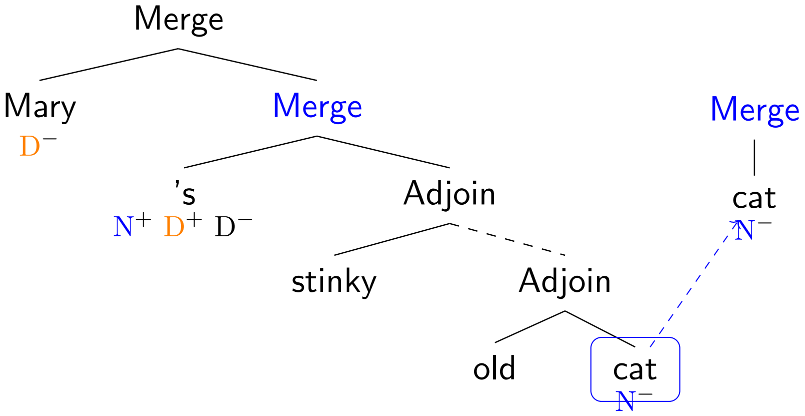

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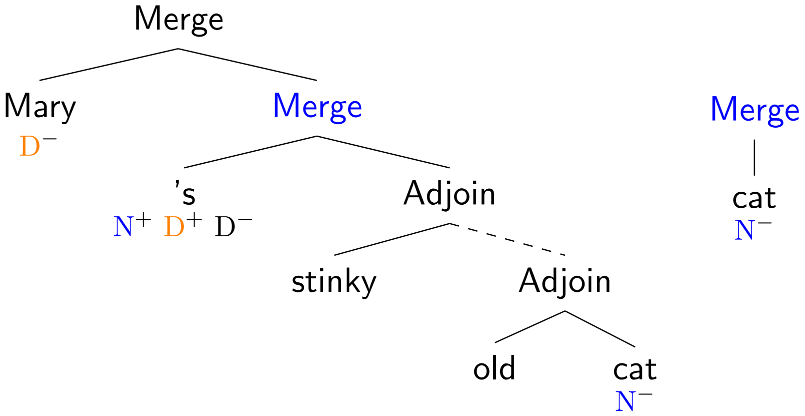

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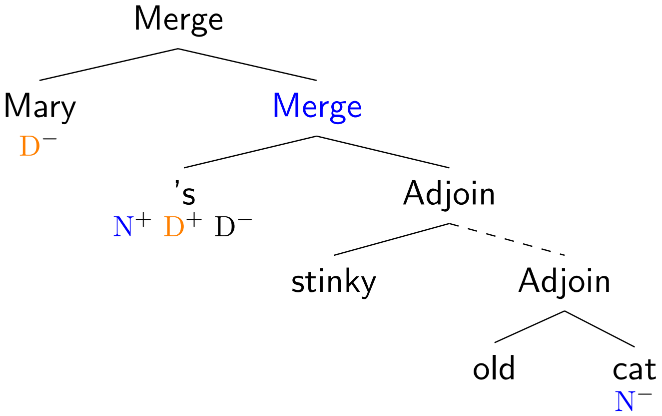

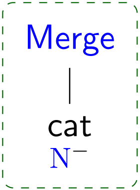

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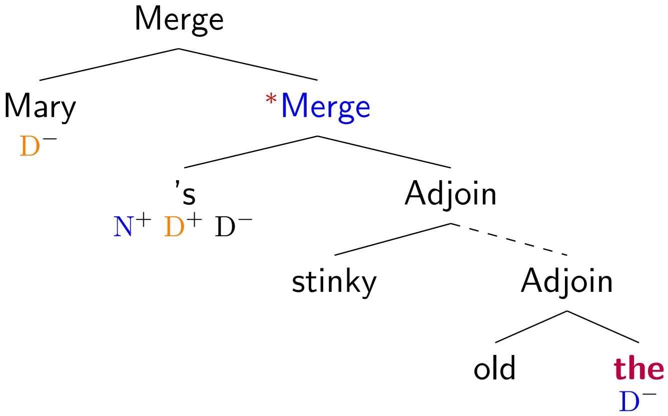

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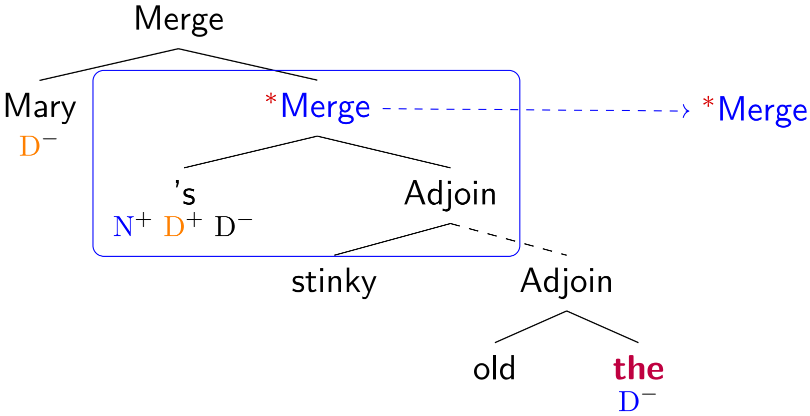

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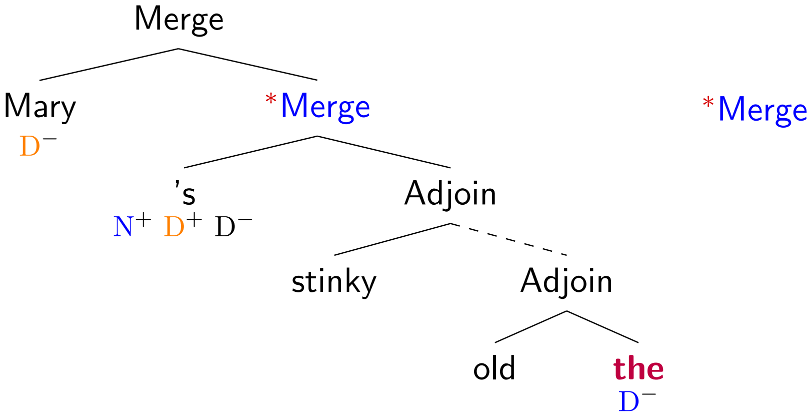

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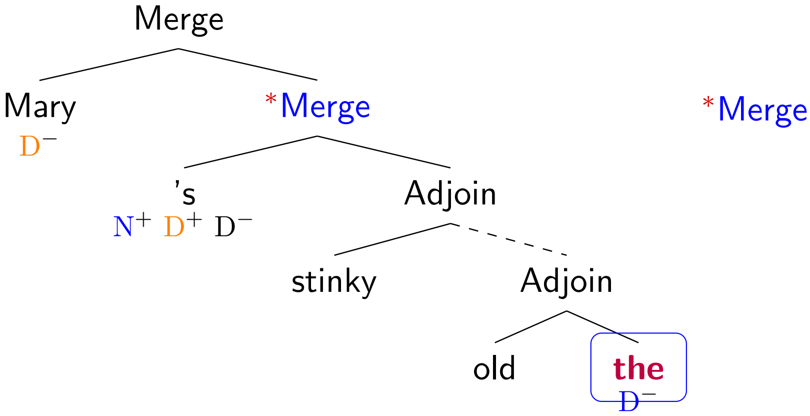

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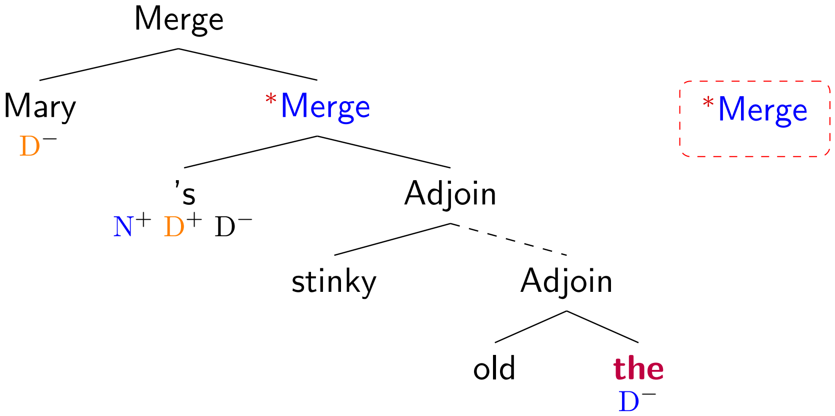

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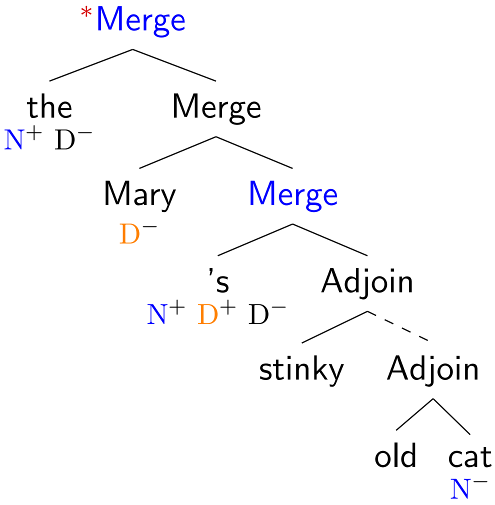

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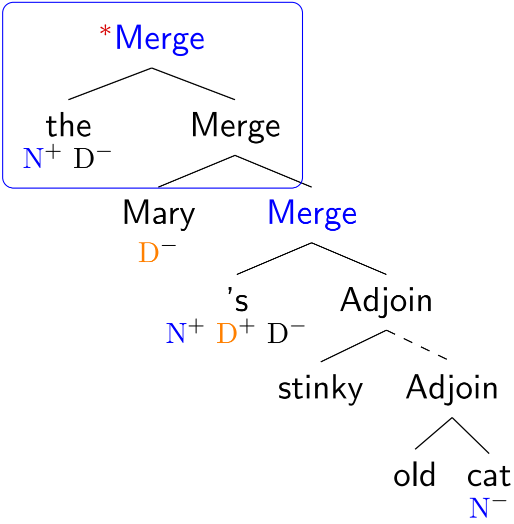

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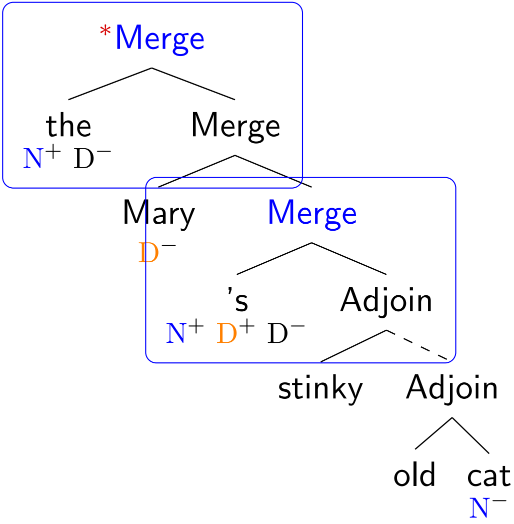

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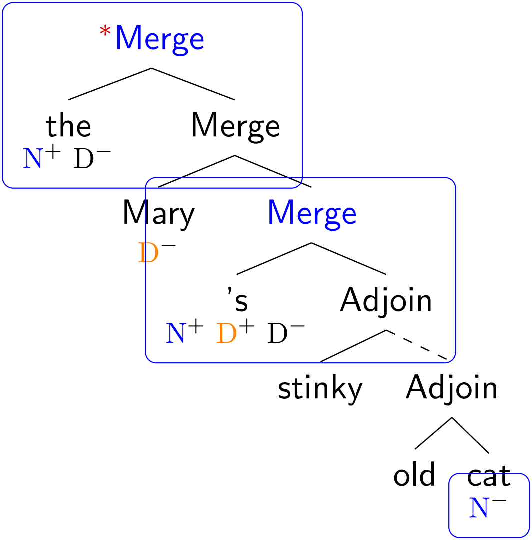

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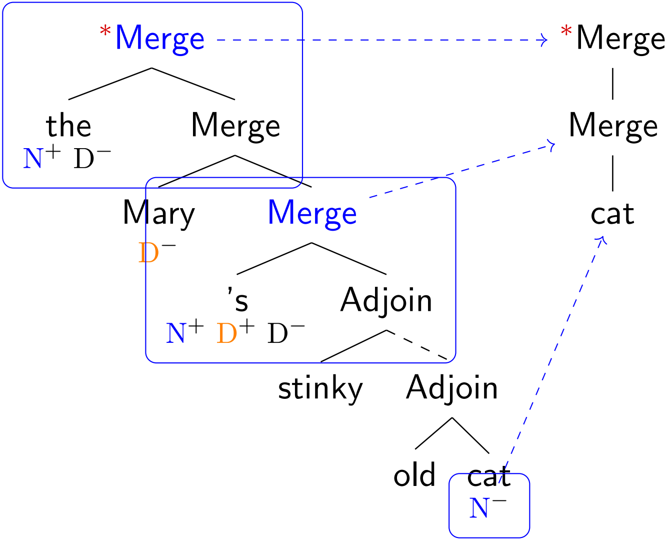

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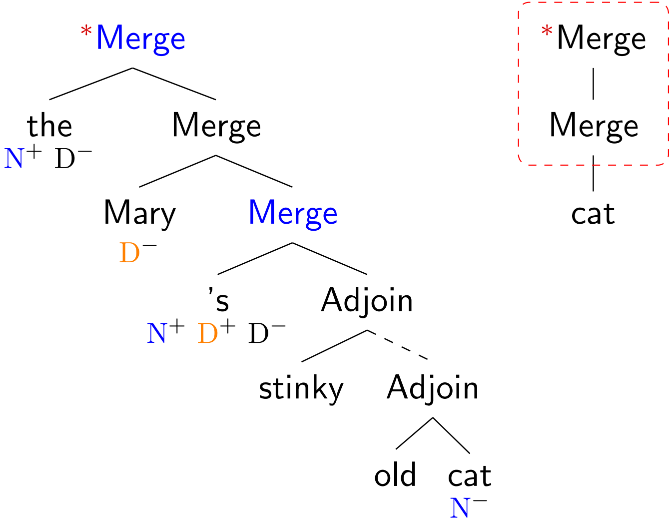

Constraints on Move

What about Move?

Suppose our MG is in **single movement normal form**, i.e. every phrase moves at most once.
Then movement is regulated by two constraints. (Graf 2012)

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Tiers for Movement

- There is no upper bound on the distance between a lexical item and its matching Move node.
- Consequently, **Move dependencies are not local**.
- What if every movement type (wh, topic, ...) induces its own tier? Would that make Move dependencies local?

Tiers for Movement

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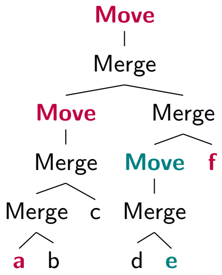

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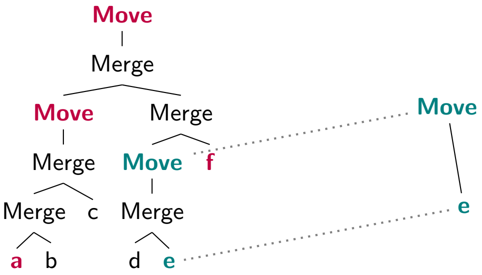

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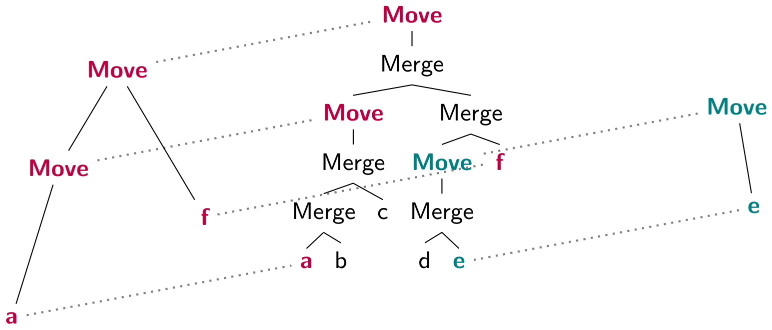

Move Constraints over Tiers

	Original	**Tier**
Move	Every head with a negative Move feature is dominated by a matching Move node.	Every lexical item has a **mother** labeled Move.
SMC	Every Move node is a closest dominating match for exactly one head.	Exactly one of a Move node's **daughters** is a lexical item.

Tree n-gram Templates

Move	**SMC1**	**SMC2**
\$	Move	Move
≥ 1 LI	no LI	≥ 2 LIs