Higher Order Structures in Minimalist Derivations

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Intro

Intro

Grammar formalisms, like programming languages, are useful because

> *they allow us to factor our explanation of linguistic behaviour into a statement of abstract regularities (the grammar), and a description of how these are computed online (the parser/parser-generator)*

Intro

Current MG parsing algorithms

- needlessly explode state space (making beam search implausible)
- are based on (exponentially less succinct) MCFGs
- have only extrema on GLC lattice (inherited from MCFG)

Intro

We exploit the structure of MGs
to define a MG-specific TD parsing strategy

- structures search space by 'sharing' infinite classes of items
- bringing us closer to LC

This gives a formal (very literal) reconstruction of popular psycholinguistic ideas about the human sentence processing mechanism

MGs

Overview

a formalization of Chomsky's "minimalist program"

- I think they are an *exact* formalization
- I am interested in them because they are a bridge between linguistics and computer science

Properties

MGs belong to family of MCS grammar formalisms

- TAG is Monadic CFTG, and MG is (contained in) MRTG
  - Share the regularity of derivation trees
- TALs are all *well-nested* MCFLs, but MLs are the non-well-nested MCFLs
  separation: (Kanazawa & Salvati, 2010)

$$\{w\#w \mid w \in L,\ L \text{ is in } CFL - EDT0L\}$$

well-nested MCFLs can have crossing dependencies, but not between syntactically complicated objects

Minimalist Grammars

- To specify a grammar, we need to specify two things:
  1. The features
     (which features we will use in our grammar)
  2. The lexicon
     (which syntactic feature sequences are assigned to which words)

Features

Features come in pairs

- `=x` and `x`
- `+y` and `-y`

Like in CG, categories are *structured*

- list of features

tradition calls categories: *feature bundles*

`=n.d.-k`

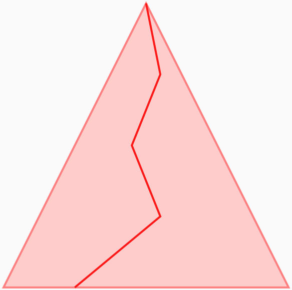
Data structure

Binary branching trees

- internal node labels: > and <
- leaf labels: (w, δ) and `t`

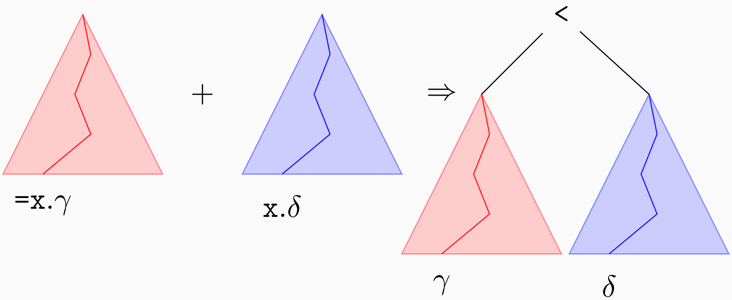
Headed trees

```
head( >(u,v) ) = head( v )
head( <(u,v) ) = head( u )
head( l ) = l
```

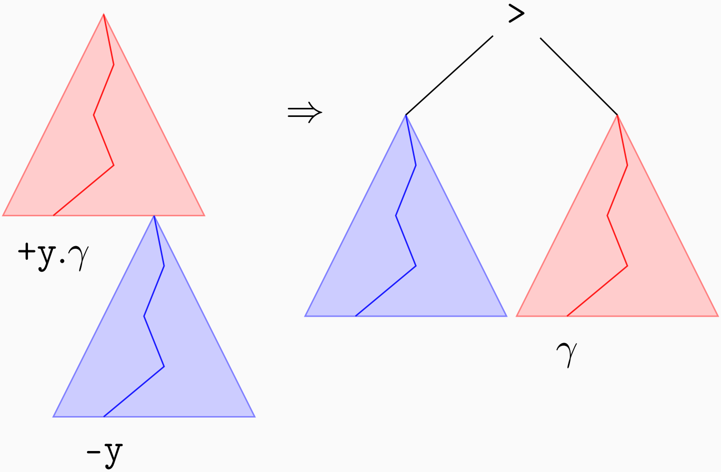


δ

Merge



Move



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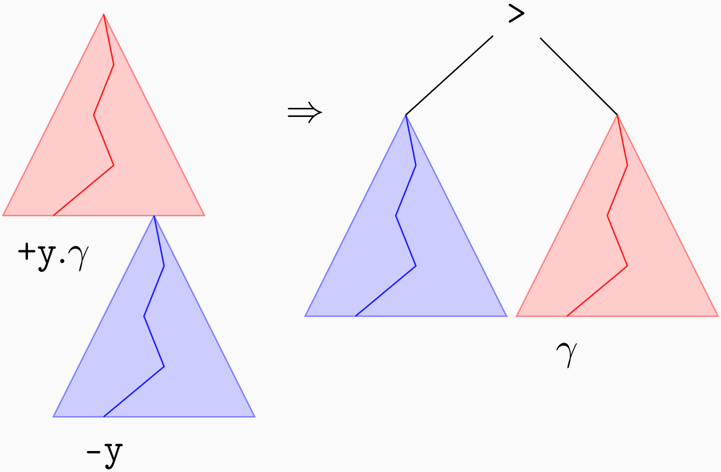


SMC
No other possible mover

A working example

boy	`n`
every	`=n.d.-k`
laugh	`=d.v`
will	`=v.+k.s`

Representing derivations

Representing derivations

1. `select` *every*

every

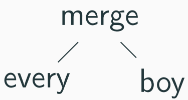
Representing derivations

1. `select` *every*
2. `select` *boy*

every boy

Representing derivations

1. `select` *every*
2. `select` *boy*
3. `merge` *1* and *2*
   $[_{DP}$ every $[_{NP}$ boy]]



Representing derivations

1. `select` *every*
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3. `merge` *1* and *2*
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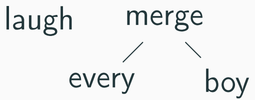
4. `select` *laugh*



Representing derivations

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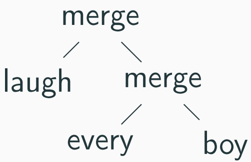
   $[_{DP}$ every $[_{NP}$ boy $]]$
4. `select` *laugh*
5. `merge` *4* and *3*
   $[_{VP}$ laugh $[_{DP}$ every boy $]]$



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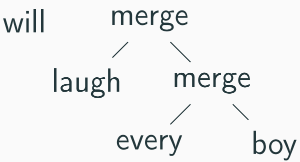
5. `merge` *4* and *3*
   $[_{VP}\ \text{laugh}\ [_{DP}\ \text{every boy}\ ]]$
6. `select` *will*



Representing derivations

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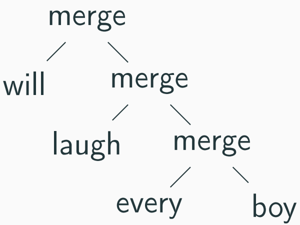
5. `merge` *4* and *3*
   $[_{VP}$ laugh $[_{DP}$ every boy $]]$
6. `select` *will*
7. `merge` *6* and *5*
   $[_{IP}$ will $[_{VP}$ laugh $[_{DP}$ every boy $]]]$



Representing derivations

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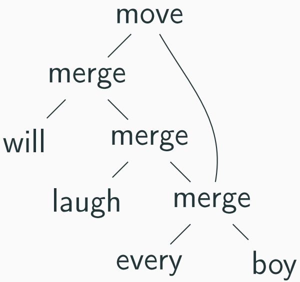
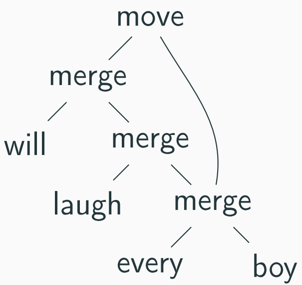
6. `select` *will*
7. `merge` *6* and *5*
   $[_{IP}$ will $[_{VP}$ laugh $[_{DP}$ every boy $]]]$
8. `move` *every boy*
   $[_{IP}[_{DP}$ every boy $][_{I'}$ will $[_{VP}$ laugh $t]]]$



The determinacy of movement



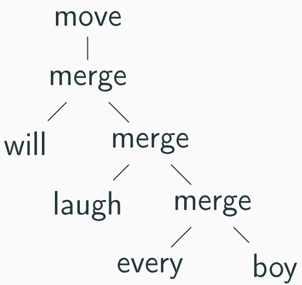
Attract Closest

Minimal Link

Shortest Move

SMC
can only be 1 thing moving for a particular reason at any time

The determinacy of movement



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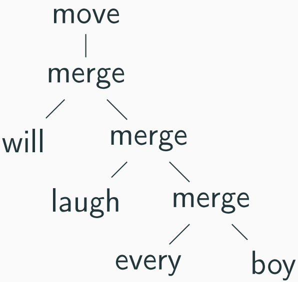
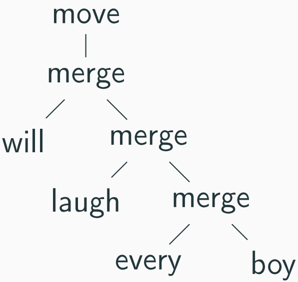


The proof objects of minimalism

- are *first order* (i.e. trees)

The determinacy of movement



The proof objects of minimalism

- are *first order* (i.e. trees)
- the proofs of any proposition (e.g. S) form a *regular tree language*

Towards MCFGs (I.)

- a *categorized string* is a pair $\phi = (u, \delta)$, where

  $\mathbf{u}$ is a string

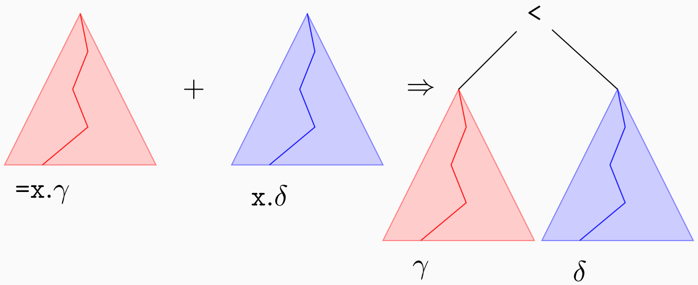
  δ is a feature bundle

- an *expression* is a finite sequence of categorized strings

$$\phi_0, \ldots, \phi_n$$

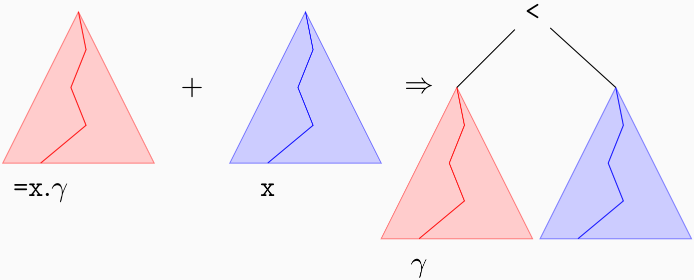
  - each $\phi_i, 1 \leq i \leq n$ represents a moving subtree
  - ϕ_0 represents the rest of the tree

Towards MCFGs (II.)



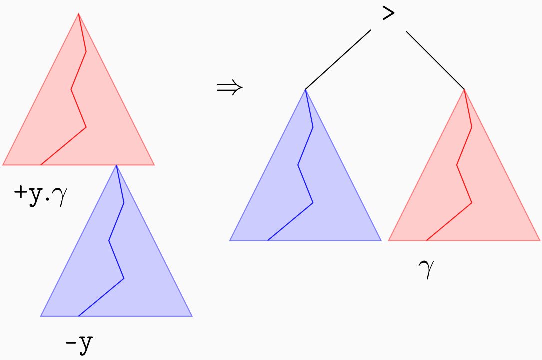
$$\frac{(u, \texttt{=x}.\gamma), \phi_1, \ldots, \phi_m \qquad (v, \texttt{x}.\delta), \psi_1, \ldots, \psi_n}{(u, \gamma), \phi_1, \ldots, \phi_m, (v, \delta), \psi_1, \ldots, \psi_n}$$

Towards MCFGs (II.)



$$\frac{(u, \texttt{=x}.\gamma), \phi_1, \ldots, \phi_m \qquad (v, \texttt{x}), \psi_1, \ldots, \psi_n}{(uv, \gamma), \phi_1, \ldots, \phi_m, \psi_1, \ldots, \psi_n}$$

Towards MCFGs (III.)



$$\frac{(u, \texttt{+y}.\gamma), \phi_1, \ldots, \phi_{j-1}, (v, \texttt{-y}), \phi_{j+1}, \ldots, \phi_m}{(vu, \gamma), \phi_1, \ldots, \phi_{j-1}, \phi_{j+1}, \ldots, \phi_m}$$

Automata

An rule like:

$$\frac{(u, \texttt{+y}.\gamma), \phi_1, \ldots, \phi_{j-1}, (v, \texttt{-y}), \phi_{j+1}, \ldots, \phi_m}{(vu, \gamma), \phi_1, \ldots, \phi_{j-1}, \phi_{j+1}, \ldots, \phi_m}$$

gives us an *ldmbutts (tree-to-string)* production:

$$\begin{aligned} &\mathrm{move}(q(u, v_1, \ldots, v_{j-1}, v, v_{j+1}, \ldots, v_m)) \\ &\qquad \to q'(vu, v_1, \ldots, v_{j-1}, v_{j+1}, \ldots, v_m) \end{aligned}$$

where

$$\begin{aligned} q &= \langle \texttt{+y}.\gamma, \delta_1, \ldots, \delta_{j-1}, \texttt{-y}, \delta_j, \ldots, \delta_m \rangle \\ q' &= \langle \gamma, \delta_1, \ldots, \delta_{j-1}, \delta_j, \ldots, \delta_m \rangle \end{aligned}$$

An example

An example

every

$\big(\text{every}, = \texttt{n.d.-k}\big)$

An example

every boy

(every, $=\mathtt{n}.\mathtt{d}.\mathtt{-k}$) (boy, $\mathtt{n}$)

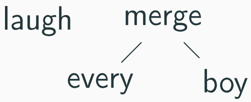
An example

merge

every boy

$$\frac{(\text{every}, \mathtt{=n.d.-k}) \qquad (\text{boy}, \mathtt{n})}{(\text{every boy}, \mathtt{d.-k})}$$

An example



$$(\text{laugh}, =\mathtt{d}.\mathtt{v}) \qquad \frac{(\text{every}, =\mathtt{n}.\mathtt{d}.\text{-}\mathtt{k}) \qquad (\text{boy}, \mathtt{n})}{(\text{every boy}, \mathtt{d}.\text{-}\mathtt{k})}$$

An example

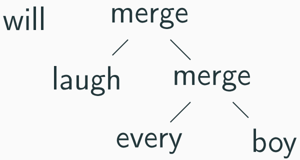
merge

laugh merge

every boy

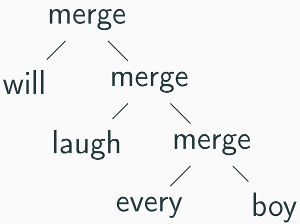
$$\dfrac{(\text{laugh}, \texttt{=d.v}) \qquad \dfrac{(\text{every}, \texttt{=n.d.-k}) \qquad (\text{boy}, \texttt{n})}{(\text{every boy}, \texttt{d.-k})}}{(\text{laugh}, \texttt{v}), (\text{every boy}, \texttt{-k})}$$

An example



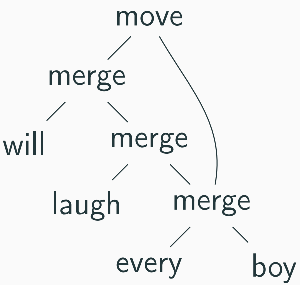
$$(\text{will}, \texttt{=v.+k.s}) \qquad \dfrac{(\text{laugh}, \texttt{=d.v}) \qquad \dfrac{(\text{every}, \texttt{=n.d.-k}) \qquad (\text{boy}, \texttt{n})}{(\text{every boy}, \texttt{d.-k})}}{(\text{laugh}, \texttt{v}), (\text{every boy}, \texttt{-k})}$$

An example



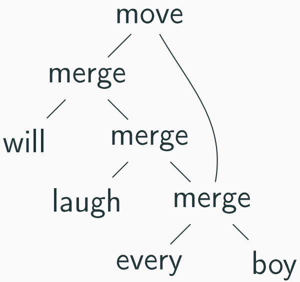
$$\dfrac{(\text{will}, \texttt{=v.+k.s}) \qquad \dfrac{(\text{laugh}, \texttt{=d.v}) \qquad \dfrac{(\text{every}, \texttt{=n.d.-k}) \qquad (\text{boy}, \texttt{n})}{(\text{every boy}, \texttt{d.-k})}}{(\text{laugh}, \texttt{v}), (\text{every boy}, \texttt{-k})}}{(\text{will laugh}, \texttt{+k.s}), (\text{every boy}, \texttt{-k})}$$

An example



$$\dfrac{\dfrac{(\text{will}, \texttt{=v.+k.s}) \qquad \dfrac{(\text{laugh}, \texttt{=d.v}) \qquad \dfrac{(\text{every}, \texttt{=n.d.-k}) \qquad (\text{boy}, \texttt{n})}{(\text{every boy}, \texttt{d.-k})}}{(\text{laugh}, \texttt{v}), (\text{every boy}, \texttt{-k})}}{(\text{will laugh}, \texttt{+k.s}), (\text{every boy}, \texttt{-k})}}{(\text{every boy will laugh}, \texttt{s})}$$

An example

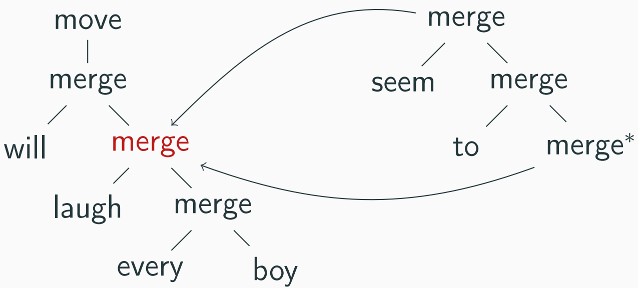


$$\dfrac{(\text{will}, \texttt{=v.+k.s}) \qquad \dfrac{(\text{laugh}, \texttt{=d.v}) \qquad \dfrac{(\text{every}, \texttt{=n.d.-k}) \qquad (\text{boy}, \texttt{n})}{(\text{every boy}, \texttt{d.-k})}}{(\text{laugh}, \texttt{v}), (\text{every boy}, \texttt{-k})}}{\dfrac{(\text{will laugh}, \texttt{+k.s}), (\text{every boy}, \texttt{-k})}{(\text{every boy will laugh}, \texttt{s})}}$$

A slightly larger example

boy	`n`
every	`=n.d.-k`
laugh	`=d.v`
will	`=v.+k.s`
to	`=v.i`
seem	`=i.v`

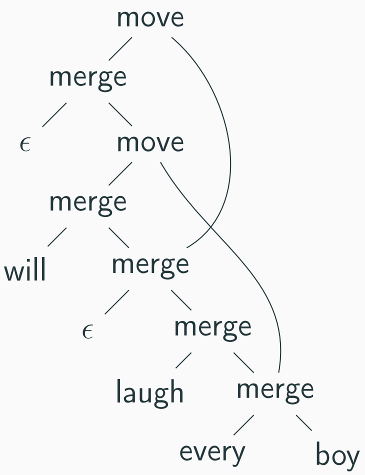
More derivations



Yoda

boy	`n`
every	`=n.d.-k`
laugh	`=d.v`
will	`=v.+k.s`
to	`=v.i`
seem	`=i.v`
ϵ	`=v.v.-top`
ϵ	`=s.+top.c`

Remnant movement



Parsing

Top-down parsing

Items represent cuts of derivation tree

$$\square$$

Top-down parsing

Items represent cuts of derivation tree

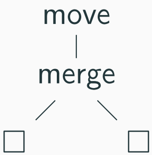
move

|

$\square$

Top-down parsing

Items represent cuts of derivation tree



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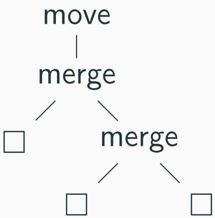

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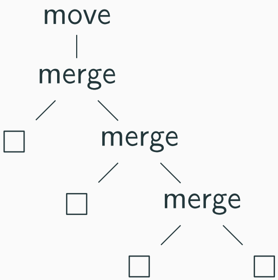

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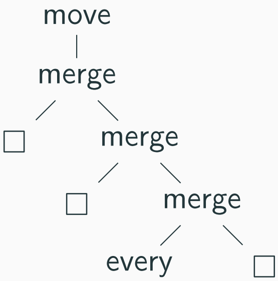

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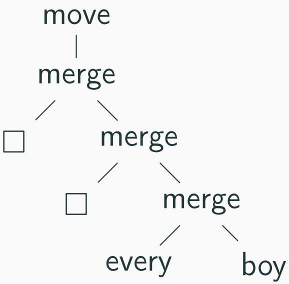

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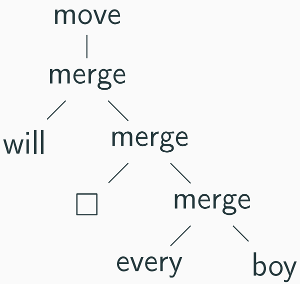

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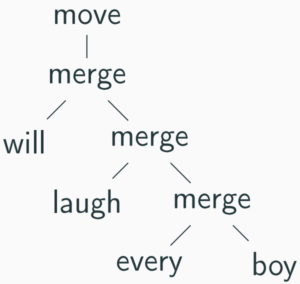

Local trees

this exploits:
MG derivation trees form a local set

$\boxed{\mathtt{S}}$

Local trees

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move

$\boxed{\texttt{+k.s;-k}}$

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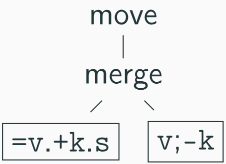

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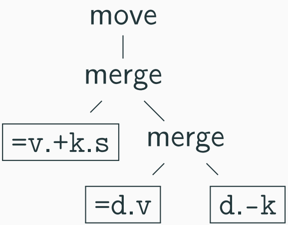

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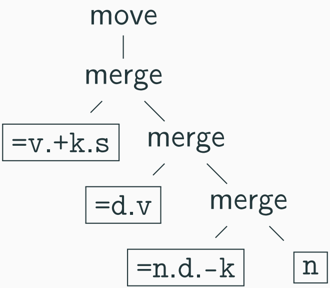

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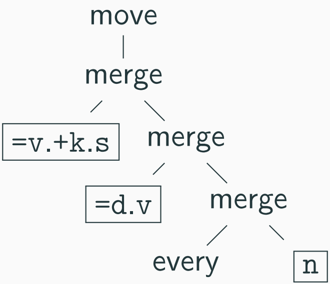

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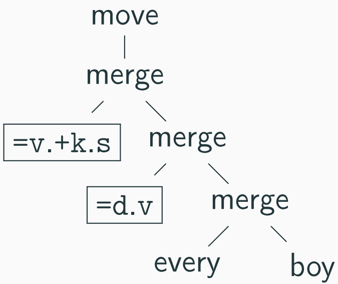

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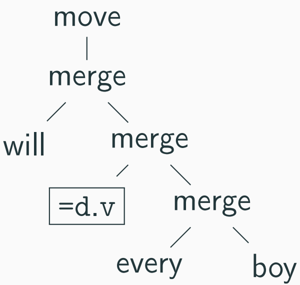

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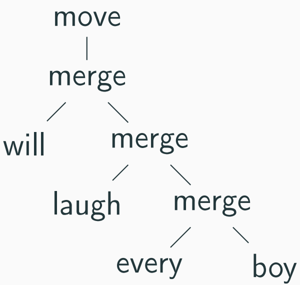

Undoing movement

- When we hypothesize a move node:

move

|

$\boxed{\texttt{+k.s;-k}}$

Undoing movement

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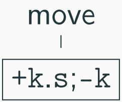
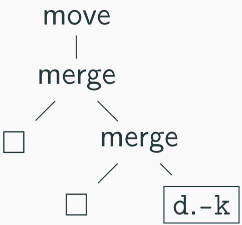
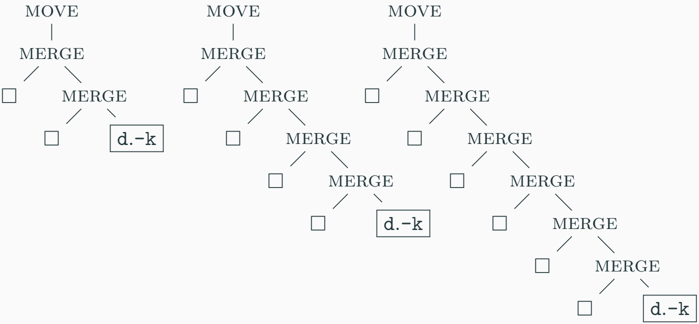


- We next must hypothesize where the mover is:

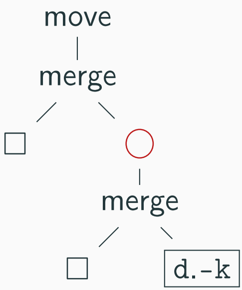


Appearances can be deceiving

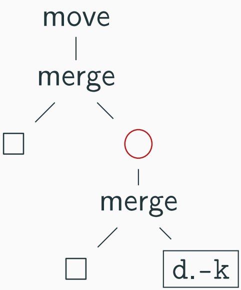
Every boy will (seem to) laugh*



If only. . .



If only. . .



- Might work in this case,
  - but is there a non-analysis specific principle?

Structure in derivations

MG derivations are *subregular* **(Graf)**
(Tier-based) strictly local

strict locality conjunction of negative literals
(with immediate successor)

tier-based relativized successors
($\lhd_T$, where $T \subseteq \Sigma$)

Example (strings)

Primary stress
$\lhd := \lhd_{\acute{\sigma}}$

Have primary stress $\neg(\$ \lhd \$)$

Have at most one stress $\neg(\acute{\sigma} \lhd \acute{\sigma})$

Example (trees)

Movement (Graf)
$\lhd := \lhd_{\texttt{+k},\texttt{-k}}$

Movers gonna move $\neg(\$ \lhd \ell)$

No movement without movement $\neg(\text{move} \lhd \$)$

No competition $\neg(\text{move} \lhd \ell_1, \ell_2)$

Argument structure via *n*-grams

Every lexical item ℓ appears in a derivation with a unique local context

- depends exclusively on positive feature sequence ($=\mathtt{x}$ and $+\mathtt{y}$)

$$(\text{will}, =\mathtt{v}.+\mathtt{k}.\mathtt{s})$$

Argument structure via *n*-grams

Every lexical item ℓ appears in a derivation with a unique local context

- depends exclusively on positive feature sequence (=x and +y)

merge

(will, =v.+k.s) □

Argument structure via *n*-grams

Every lexical item ℓ appears in a derivation with a unique local context

- depends exclusively on positive feature sequence ($=\mathrm{x}$ and $+\mathrm{y}$)

move

merge

(will, $=\mathrm{v}.+\mathrm{k}.\mathrm{s}$) $\square$

Exploiting regularities in derivations

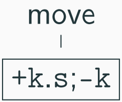
- When we hypothesize a move node:

move

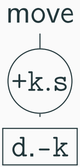
$\boxed{\texttt{+k.s;-k}}$

Exploiting regularities in derivations

- When we hypothesize a move node:



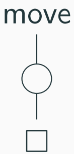
- We know it immediately dominates a mover (on the relevant tier):



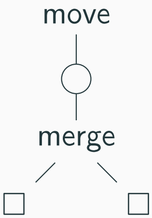
A sketch

□

A sketch



A sketch



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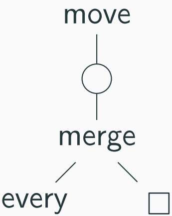

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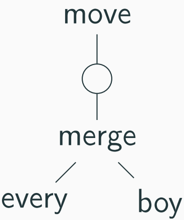

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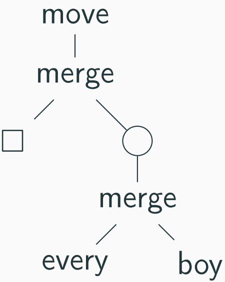

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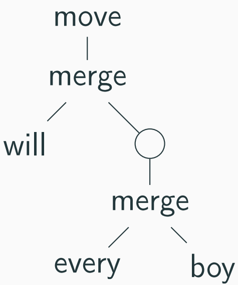

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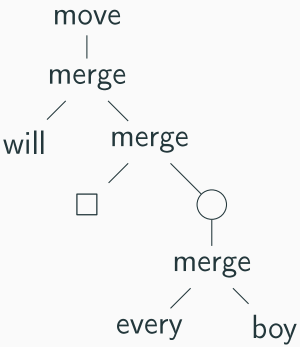

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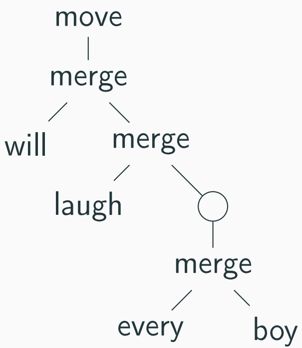
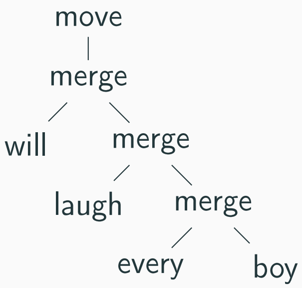


A sketch



A basic 'hole' data structure

$$\boxed{\alpha}^{g}$$
$$|$$
$$xs$$

- g is a gorn address
  where we are in the derived tree

```
data Hole t b x = Hole t [(b,x)]
```

A basic 'hole' data structure

$$\begin{array}{c} \boxed{\alpha}^{g} \\ | \\ xs \end{array}$$

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- *xs* is a (finite) list of

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  - derivations with holes
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A basic 'hole' data structure

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$$|$$
$$xs$$

- g is a gorn address
  where we are in the derived tree
- xs is a (finite) list of
  - derivations with holes
    elements in separate tiers
  - ... paired with feature bundles
    information about the occupied tier

```
data Hole t b x = Hole t [(b,x)]
```

Unmerge1

- Given

$$\begin{array}{c}\boxed{\alpha : g} \\ | \\ xs\end{array}$$

Unmerge1

- Given

$$\boxed{\alpha : g}$$

$$|$$

$$\mathit{xs}$$

- merge could have applied

merge

$$/ \quad \backslash$$

$$\boxed{=\mathrm{x}.\alpha : g0} \quad \boxed{\mathrm{x} : g1}$$

$$| \qquad\qquad |$$

$$\mathit{us} \qquad\qquad \mathit{vs}$$

Unmerge1

- Given

$$\begin{array}{c} \boxed{\alpha : g} \\ | \\ \textit{xs} \end{array}$$

- merge could have applied

$$\begin{array}{ccc} & \text{merge} & \\ / & & \backslash \\ \boxed{=\text{x}.\alpha : g0} & & \boxed{\text{x} : g1} \\ | & & | \\ \textit{us} & & \textit{vs} \end{array}$$

Unmerge1

- Given

$$\boxed{\alpha : g}$$

xs

- merge could have applied

merge

$$\boxed{=\mathrm{x}.\alpha : g0} \quad \boxed{\mathrm{x} : g1}$$

us *vs*

```
xs = sort (us ++ vs)
```

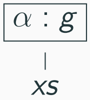
Unmove

- Given

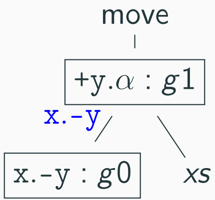
$$\begin{array}{c}\boxed{\alpha : g} \\ | \\ xs\end{array}$$

Unmove

- Given



- move could have applied



Unmerge2

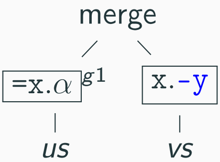
- Given

$$\begin{array}{c} \boxed{\alpha}^{g} \\ | \\ xs \end{array}$$

Unmerge2

- Given

- merge could have applied to a mover



Unmerge2

- Given

$$\boxed{\alpha}^{g}$$
$$|$$
$$xs$$

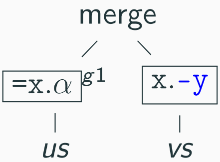
- merge could have applied to a mover

$$\text{merge}$$
$$\swarrow \qquad \searrow$$
$$\boxed{\texttt{=x.}\alpha}^{g1} \qquad \boxed{\texttt{x.-y}}$$
$$| \qquad\qquad |$$
$$us \qquad\qquad vs$$

Unmerge2

- Given

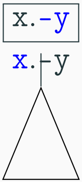
- merge could have applied to a mover




```
xs = sort (us ++ vs)
```

Completion (I)

- Given



Completion (I)

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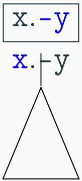
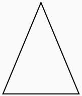


- this is the tree you're looking for

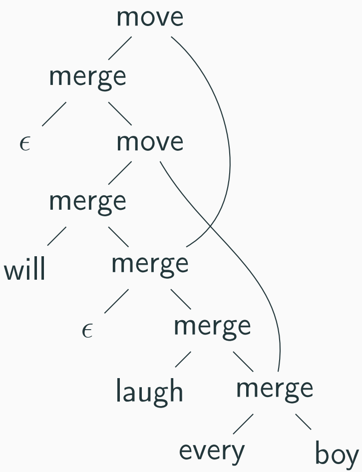


ATNs and filling gaps

- Psycholinguists
  - you process moved items (fillers)
  - and then you try to find where they moved from (gap)
- TD MG parsing

  to process filler, first find gap!
- Here
  - *unmove* constructs a filler
  - *unmerge2* constructs a gap
  - *complete* fills the gap

Remnant movement



boy	`n`
every	`=n.d.-k`
laugh	`=d.v`
will	`=v.+k.s`
ϵ	`=v.v.-top`
ϵ	`=s.+top.s`

Remnant movement

$\boxed{\text{s}}^{\epsilon}$

Remnant movement

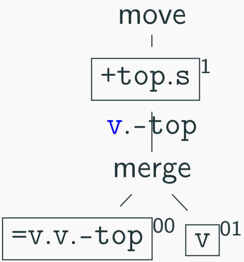
move

$\boxed{\texttt{+top.s}}^{1}$

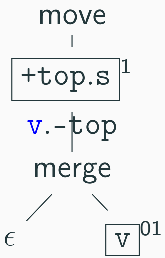
v.-top

$\boxed{\texttt{v.-top}}^{0}$

Remnant movement



Remnant movement



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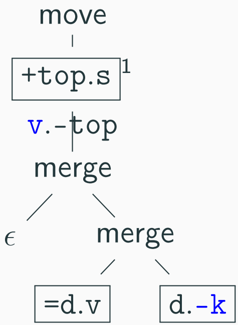

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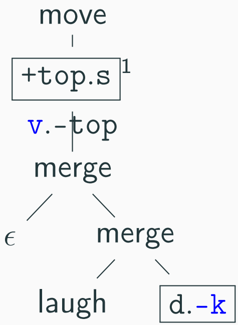

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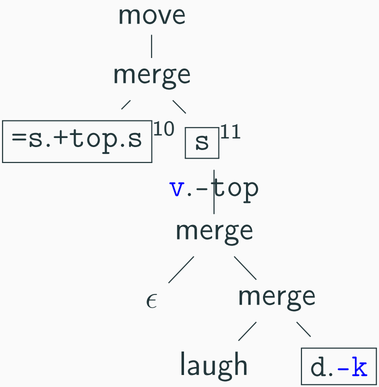
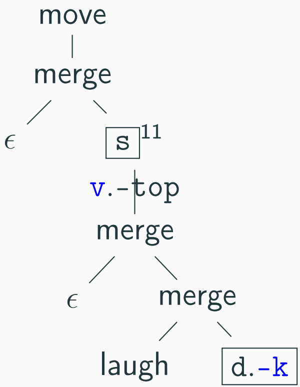
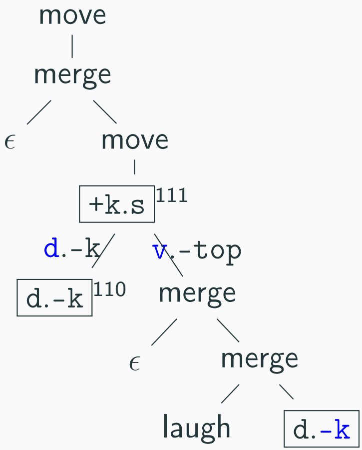


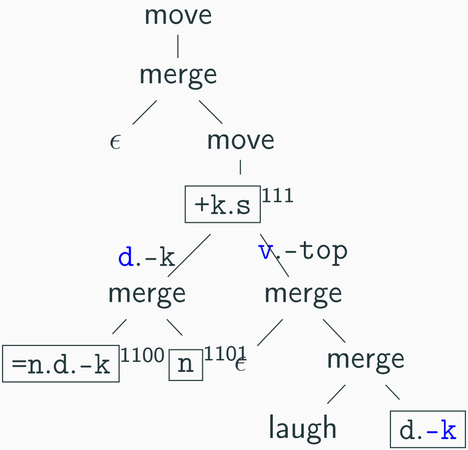
Remnant movement



Remnant movement



Remnant movement



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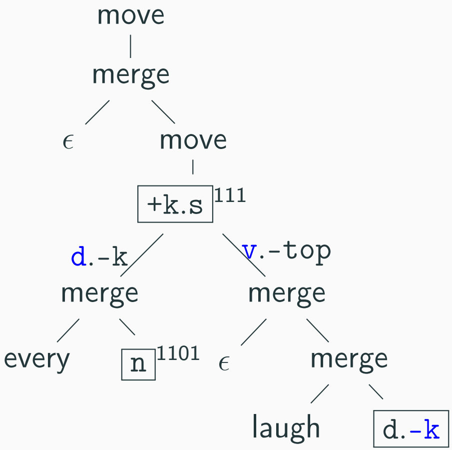

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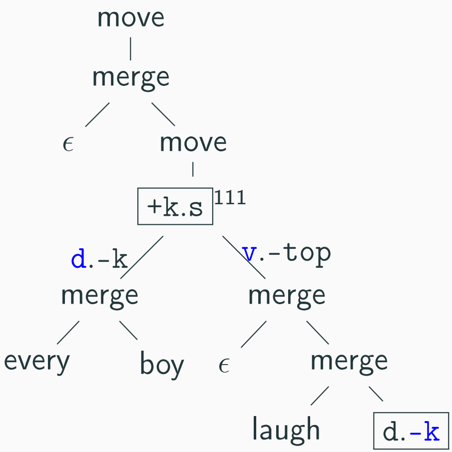

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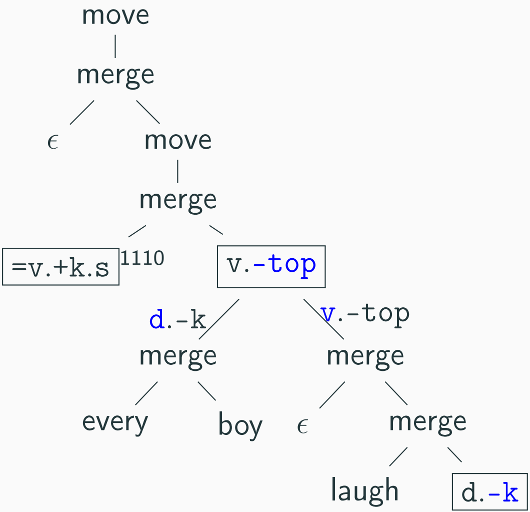

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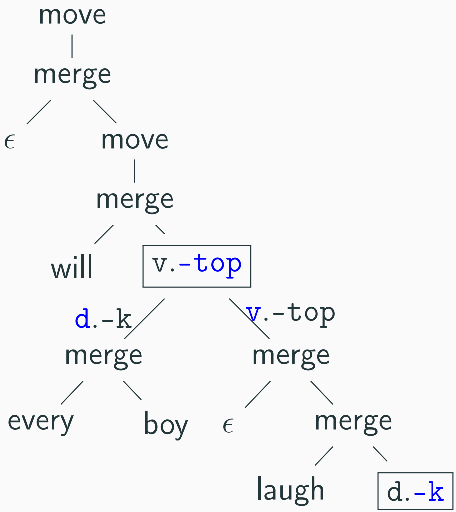

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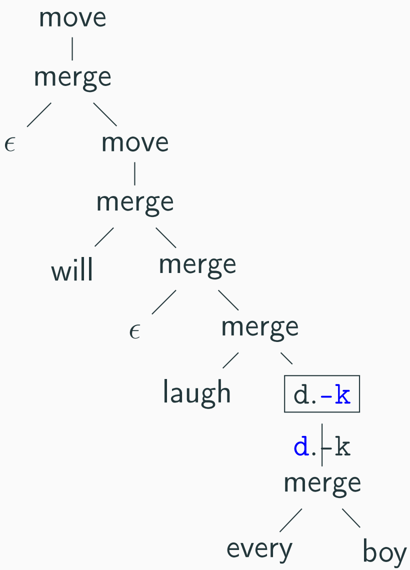
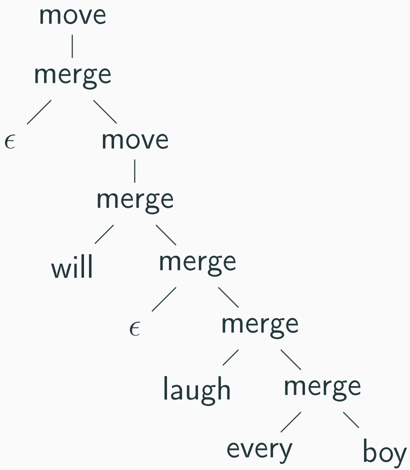


Remnant movement



Enforcing the SMC

Recall:

1. Movers gonna move : $\neg(\$ \lhd \ell)$
2. No movement without movement : $\neg(\textbf{move} \lhd \$)$
3. No competition : $\neg(\textbf{move} \lhd \ell_1, \ell_2)$

How are these being enforced?

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1. Two ways of generating a mover:

Enforcing the SMC

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How are these being enforced?

1. Two ways of generating a mover:
   - via unmerge2 (i.e. a gap) must be filled
   - via unmove (i.e. a filler) born dominated

Enforcing the SMC

Recall:

1. Movers gonna move : $\neg(\$ \lhd \ell)$
2. No movement without movement : $\neg(\mathbf{move} \lhd \$)$
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How are these being enforced?

1. Two ways of generating a mover:
2. move nodes and movers postulated simultaneously

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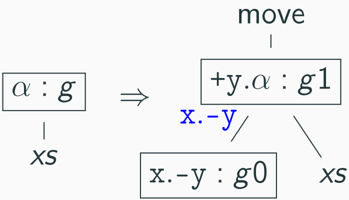
How are these being enforced?

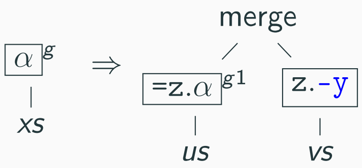
1. Two ways of generating a mover:
2. move nodes and movers postulated simultaneously
3. via restrictions

Restricting Unmove



As long as
nothing in *xs* is on the -y tier

Restricting Unmerge2



If there is something on the $-\mathrm{y}$ tier in *xs*
it must complete this gap

in other words, the $-\mathrm{y}$ tier is hereby blocked!

Completion (II)

A partial proof tree with an *n*-ary hole
is an operation of type

$$(\alpha_1 \to \cdots \to \alpha_n \to t) \to t$$

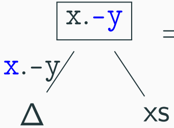
The 'α's are the types of the arguments to the hole

Upper bounds on

1. number of holes
2. their arity

depending on number of $-\mathrm{y}$ feature types in lexicon

Completion (III)



$$\Rightarrow \quad \Delta[us_1, \ldots, us_k]$$

Conditions

```
xs = sort ( us1 ++ ... ++ usk )
```

each substitution path is free for the relevant tier

A Note on Semantic Interpretation

$$[\![\textbf{merge}]\!] \mapsto \lambda m, n.(\!| m \oplus n |\!)$$

$$[\![\textbf{merge}]\!] \mapsto \lambda m, n.(\!| m \oplus \Box n |\!)$$

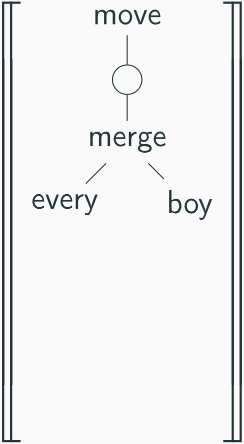
$$[\![\textbf{move}]\!] \mapsto \lambda m.m$$

$$[\![\textbf{move}]\!] \mapsto \lambda m.\langle m \rangle^{k}_{\oplus}$$

$$[\![\ell]\!] = \mathcal{I}(\ell)^{\uparrow}$$

```
(| f m n |) = do
      x <- m
      y <- n
      return (f x y)
```

The meaning of partial parse trees



$$= \lambda f_{\bigcirc}.[\![\mathit{move}]\!](f_{\bigcirc}\ ([\![\mathit{merge}]\!]\ [\![\mathit{every}]\!]\ [\![\mathit{boy}]\!]))$$

$$= \lambda f_{\bigcirc}.\langle f_{\bigcirc}\ ([\![\mathit{every}]\!]\ [\![\mathit{boy}]\!])^{\uparrow}\rangle^{k}_{FA}$$

Conclusion : Exploiting structure

- MGs have more structure in their derivations than is being made use of
  - how can we take advantage of it?
- Simple intersection w/ regular sets:

$$(\mathsf{will}, \texttt{=}^{\mathtt{r}}\mathtt{v}^{\mathtt{s}}.\texttt{+}^{\mathtt{p}}\mathtt{k}^{\mathtt{q}}.^{\mathtt{p}}\mathtt{c}^{\mathtt{s}}), \text{ where } \delta(q, \mathsf{will}) = r$$

  - how to do scheduling to obtain a version of the present algorithm?
- Left-corner parsing (for CFGs) has similar looking partial proof trees
  - can we use these ideas to get a left-corner parser for MGs and solve the problem of left branch movement?