Using Linguistic Syntax in Statistical Machine Translation

Greg Hanneman

11-731: Machine Translation
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LTI

Carnegie Mellon

Syntax in Machine Translation

What does that even mean?

Syntax in Machine Translation

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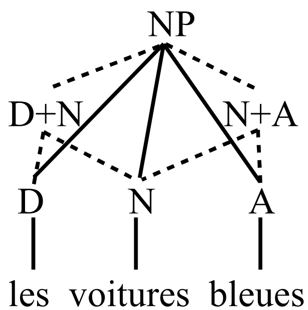
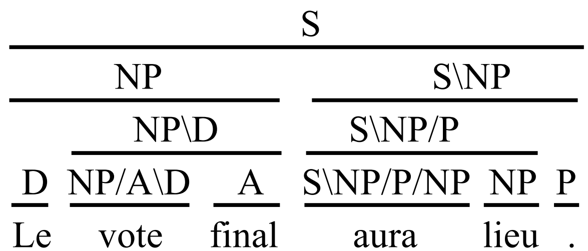
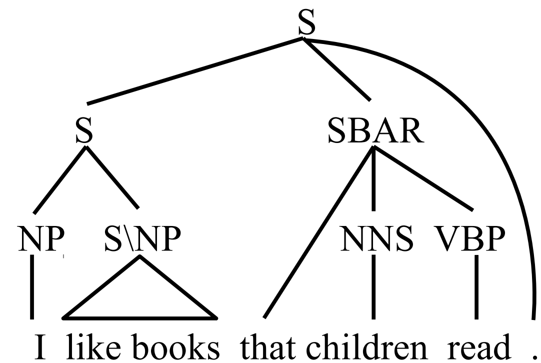
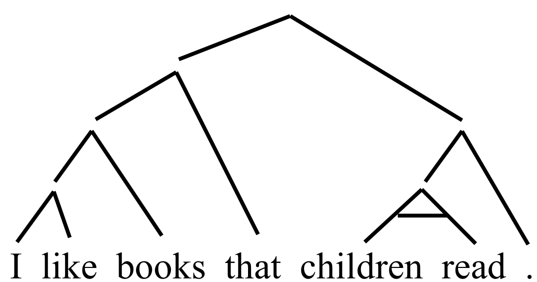
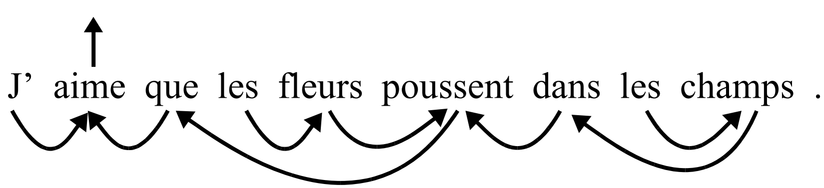
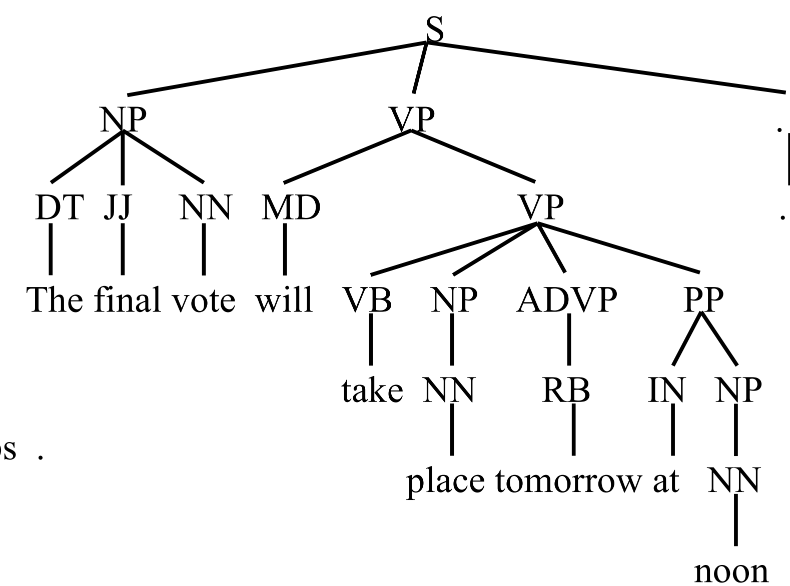












Syntax in Machine Translation

Why would we want that?

Syntax in Machine Translation

Why would we want that?

- Language is hierarchical, not finite-state!
- Generalize over different/unseen strings with same structure
- Languages have structural divergences in addition to lexical ones
- More accurate reordering at arbitrary distances

Syntax in Machine Translation

How would we make it happen?

Syntax in Machine Translation

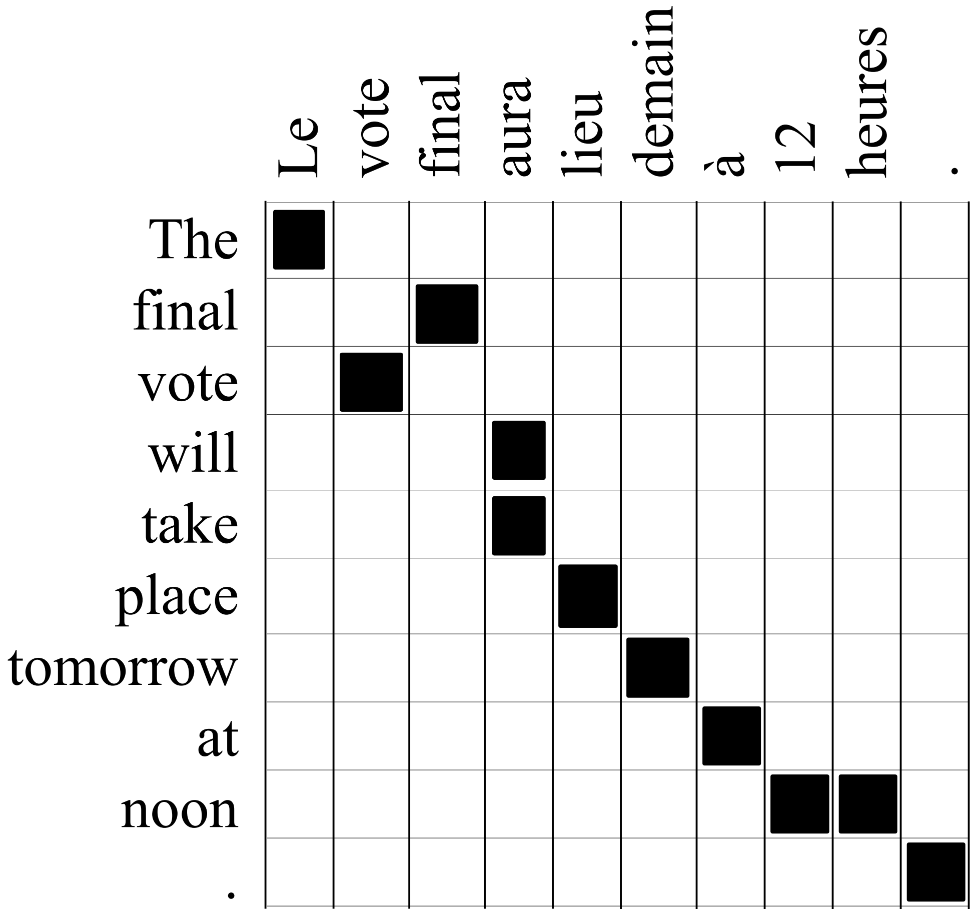
How would we make it happen?

- What notion of syntax?
- Syntax on source, target, or both?
- What do the rules look like?
- What do the labels look like?
- Input is string, tree, or forest?
- Decode bottom-up or top-down?

Syntax in Machine Translation

Side(s)	Rules	Labels	Input	Technique(s)
Source	SCFG	Treebank	Tree	Yamada and Knight [2001]
Source	STSG	Treebank	Tree	Huang et al. [2006], Liu et al. [2006]
Source	STSG	Treebank	Forest	Mi et al. [2008]
Target	SCFG	Treebank + combinations	String	Zollmann & Venugopal [2006]
Target	SCFG	"X" with soft preferences	String	Venugopal et al. [2009]
Target	STSG	Treebank	String	Galley et al. [2004]
Target	SCFG	Syntactic "X" with soft prefs	String	Huck et al. [2014]
Both	STSG	Bi-treebank	Tree	Xia and McCord [2004]
Both	SCFG	Bi-treebank	String	Lavie et al. [2008]
Both	STSG	Bi-treebank	Forest	Liu et al. [2009]
Both	SCFG	Bi-treebank + virtual nodes	String	Hanneman et al. [2011]
Both	SCFG	Bi-treebank + combinations, with soft matches	String	Chiang [2010]

Baseline: Hiero



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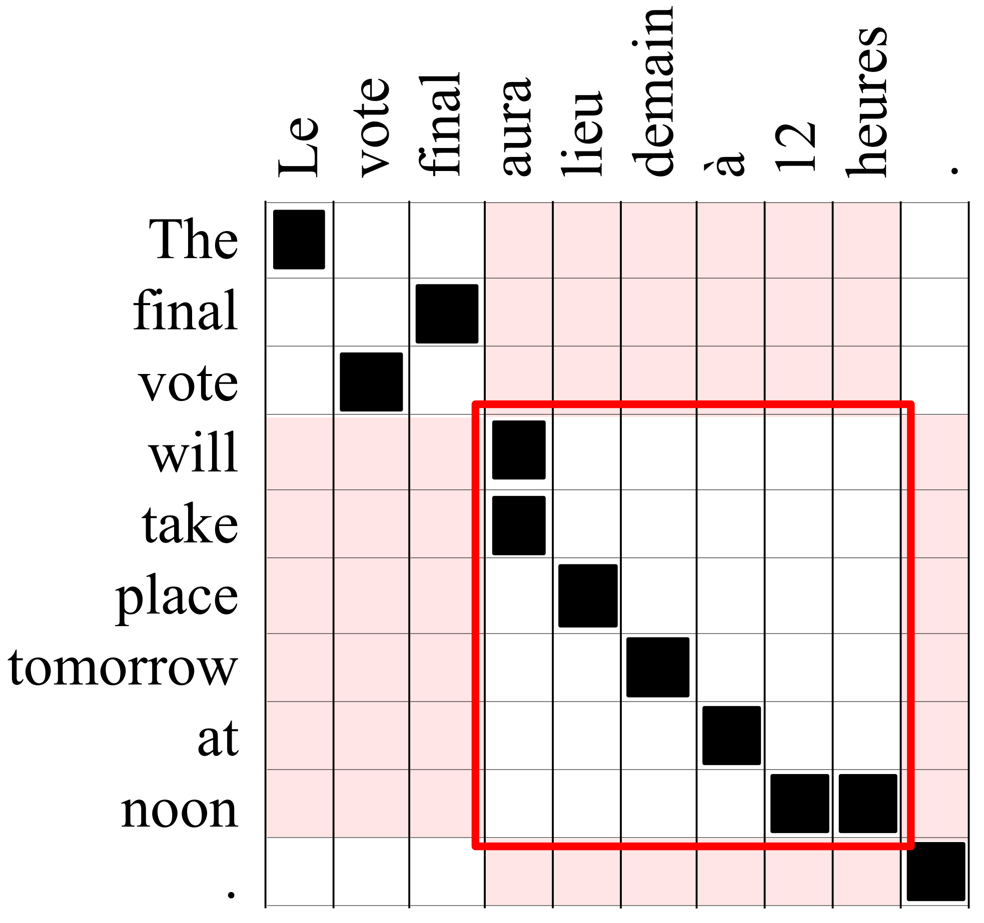
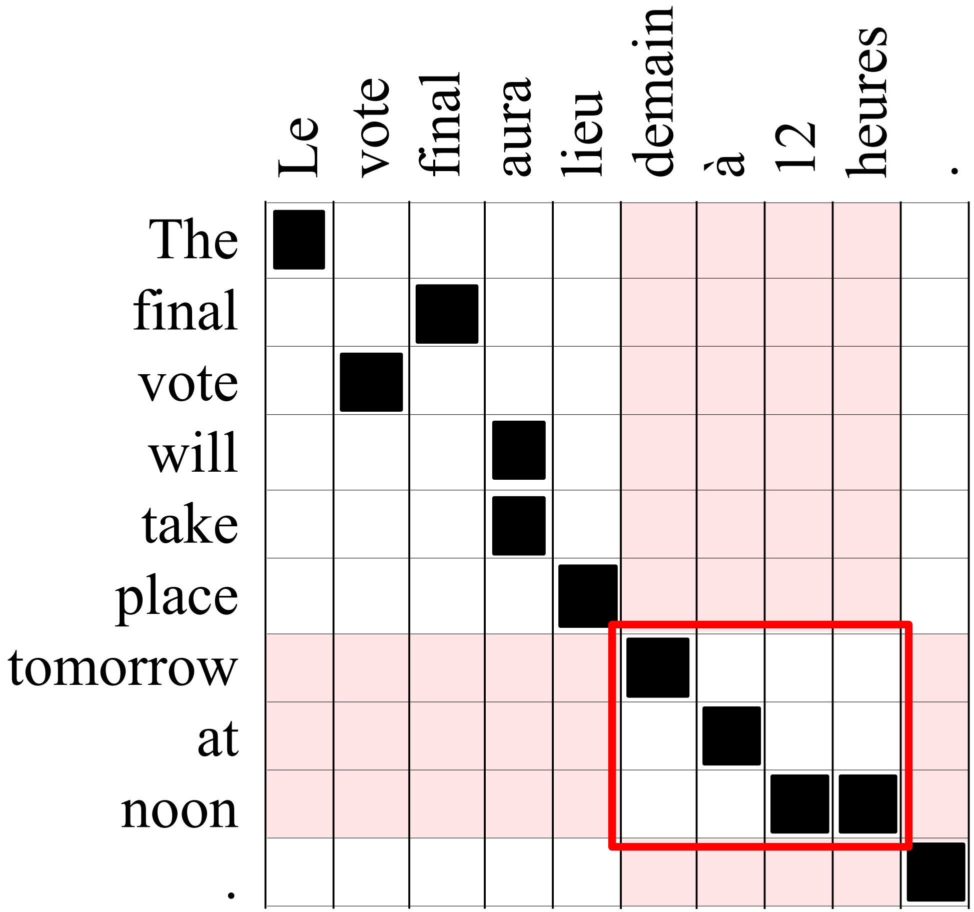


X → [aura lieu demain à 12 heures]::[will take place tomorrow at noon]

Baseline: Hiero



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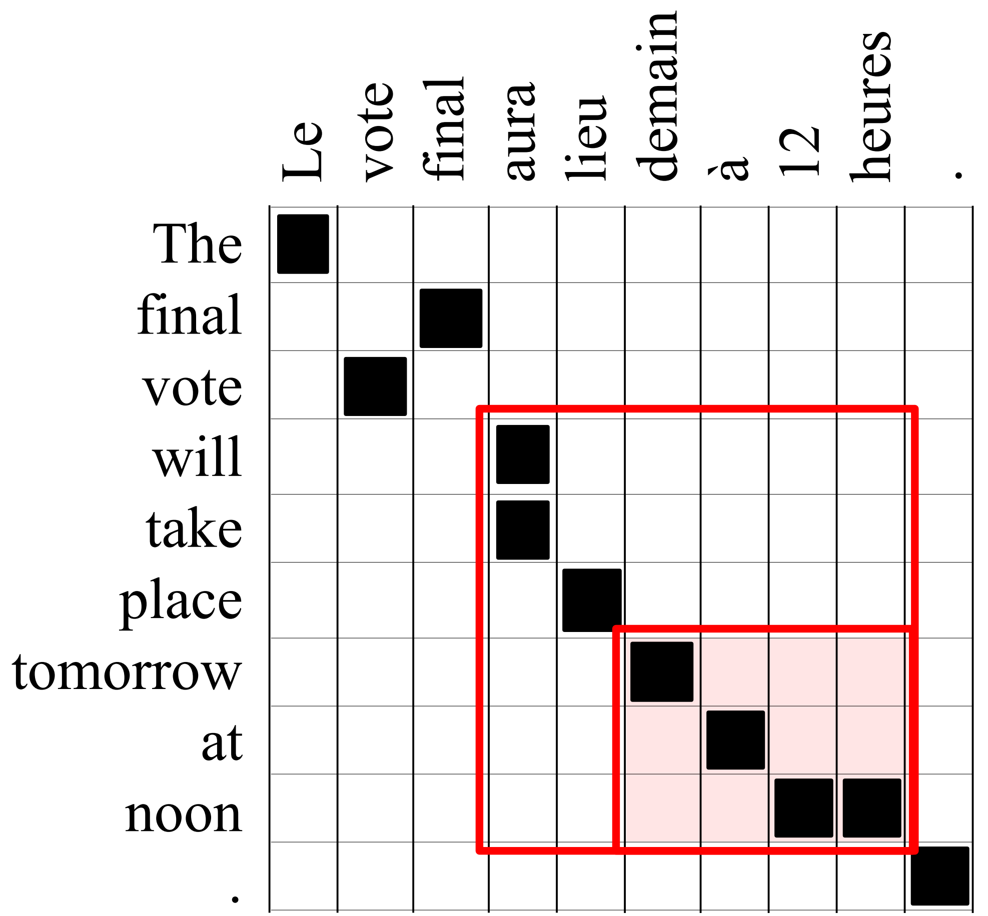
Baseline: Hiero



X → [aura lieu demain à 12 heures]::[will take place tomorrow at noon]

X → [demain à 12 heures]::[tomorrow at noon]

X → [aura lieu X_1]::[will take place X_1]

Hiero Pros and Cons

- Synchronous context-free grammar (SCFG)
- Easy to get given basic phrase extraction
- Sometimes works quite well

$$X \rightarrow [\text{que } X_1 \text{ les } X_2]::[\text{that } X_2\ X_1]$$

J' aime les livres que lisent les enfants .

I like books that children read .

✓

Hiero Pros and Cons

- Synchronous context-free grammar (SCFG)
- Easy to get given basic phrase extraction
- But sometimes doesn't…

$$X \longrightarrow [\text{que } X_1 \text{ les } X_2]::[\text{that } X_2\ X_1]$$

J' aime les livres que lisent les enfants .

I like books that children read .

J' aime que les fleurs poussent dans les champs .

I like that fields flowers grow in .

The Trouble with "X"s

- Nonterminal boundaries can be anywhere
- Can extract rule in one context and apply it in another – all "X"s look the same
- "Formally but not linguistically syntactic"

Part 1

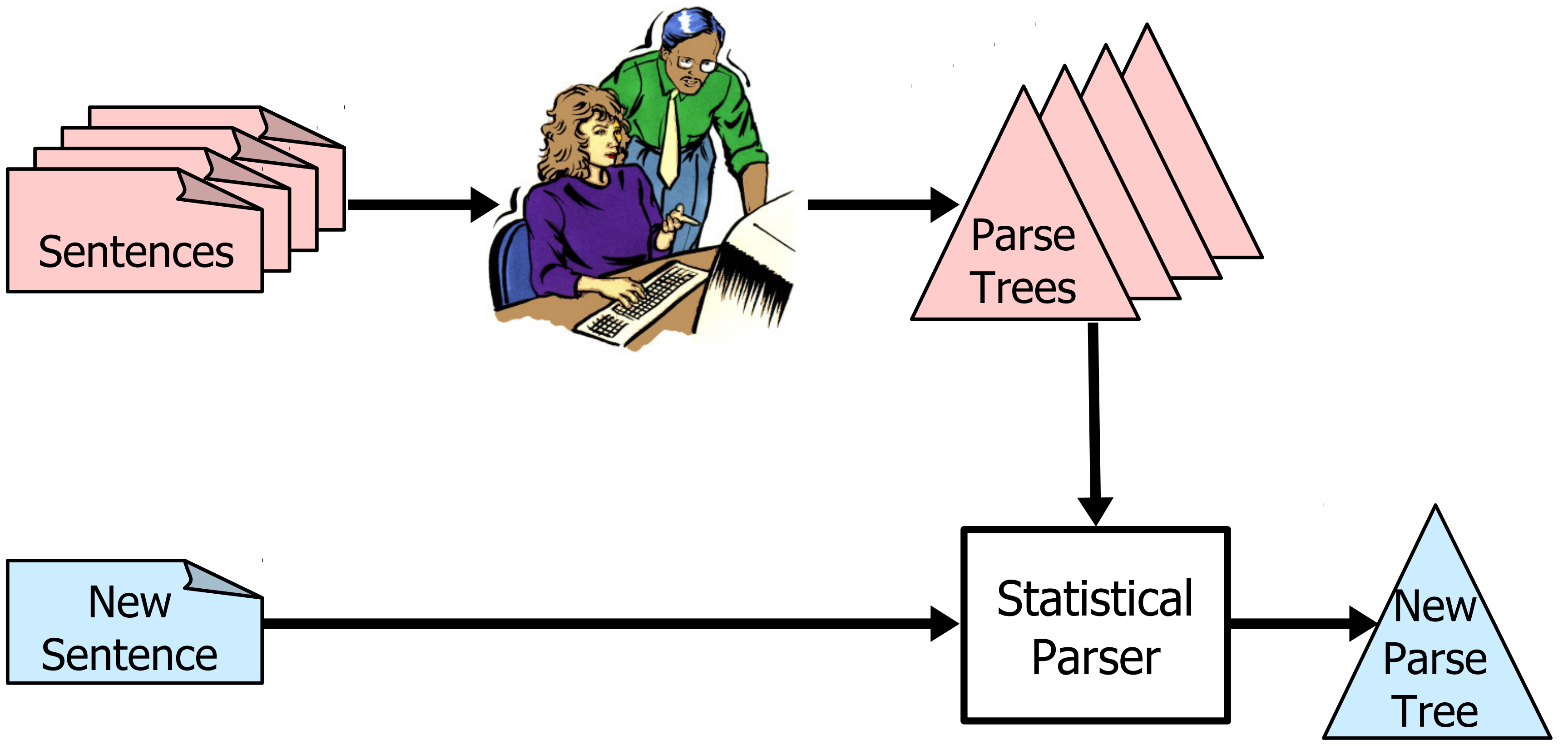
String-to-Tree Methods

“Syntax-Augmented” MT

[Zollmann and Venugopal, 2006; Zollmann, 2011]

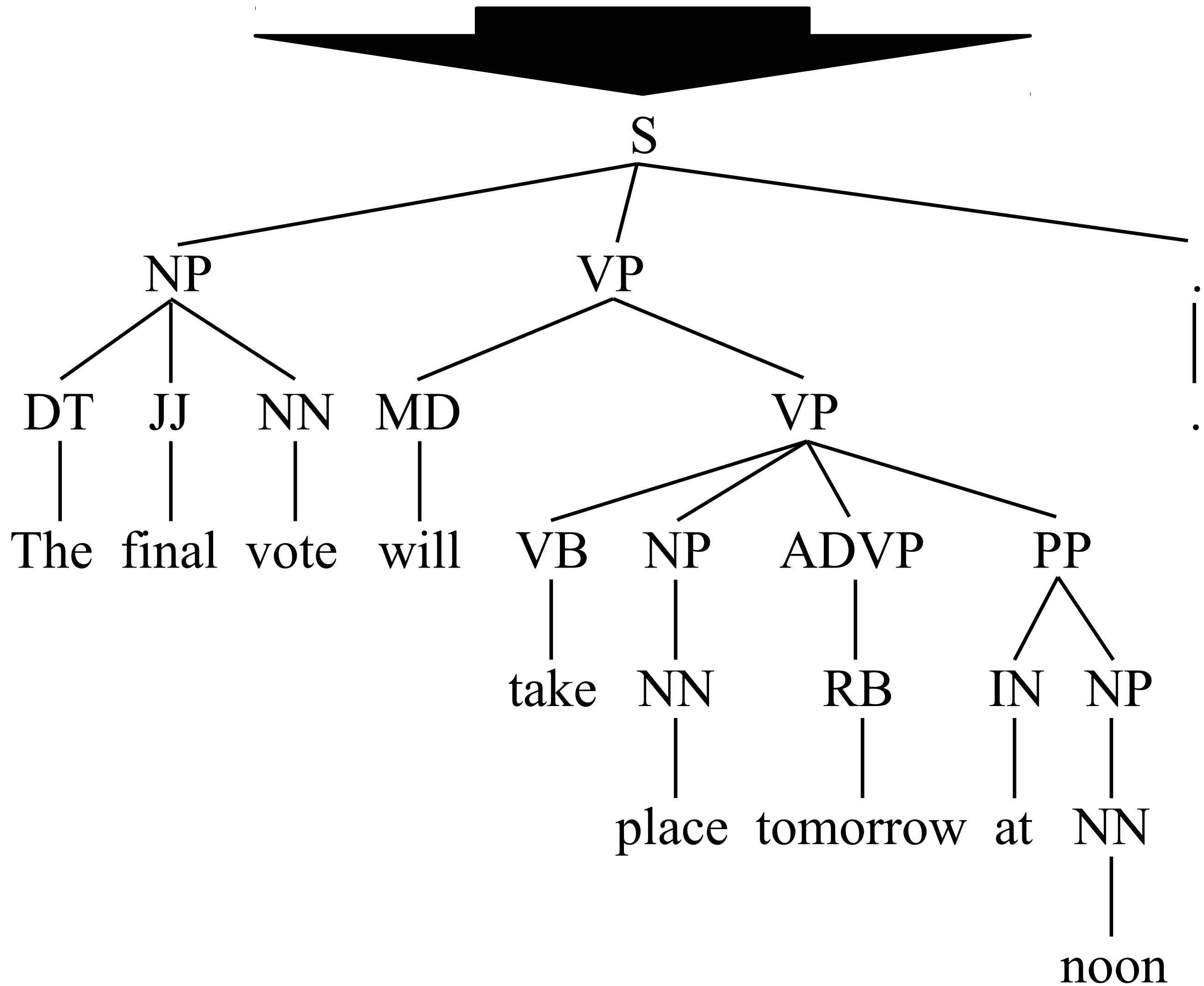
- Let’s label these Hiero rules!
- Replace “X” with labels derived from a constituency parse of the target side
- Why target?
- What about phrases that aren’t constituents? Do we lose coverage?

Aside: Statistical Parsers

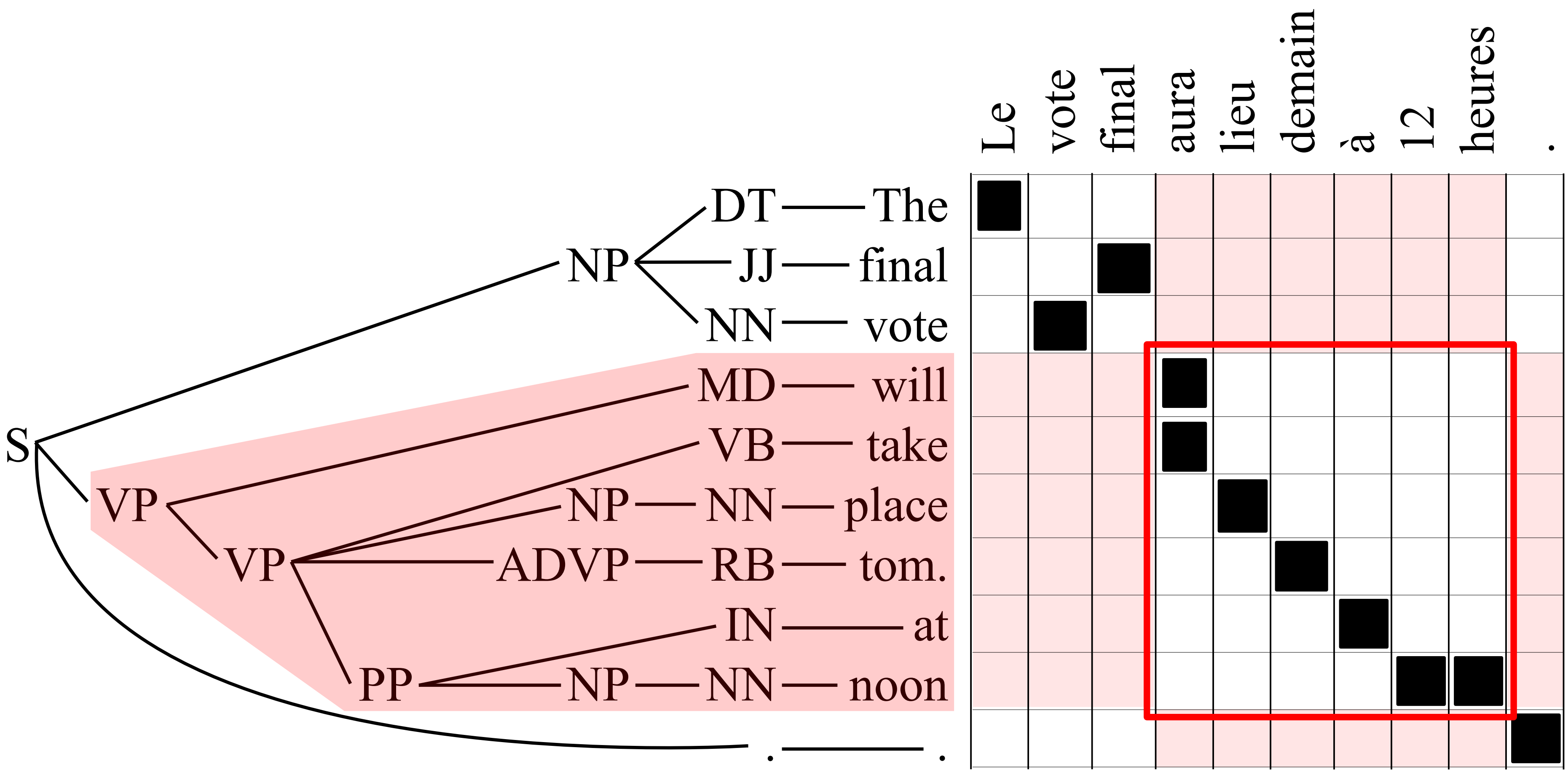


Aside: Statistical Parsers

The final vote will take place tomorrow at noon .

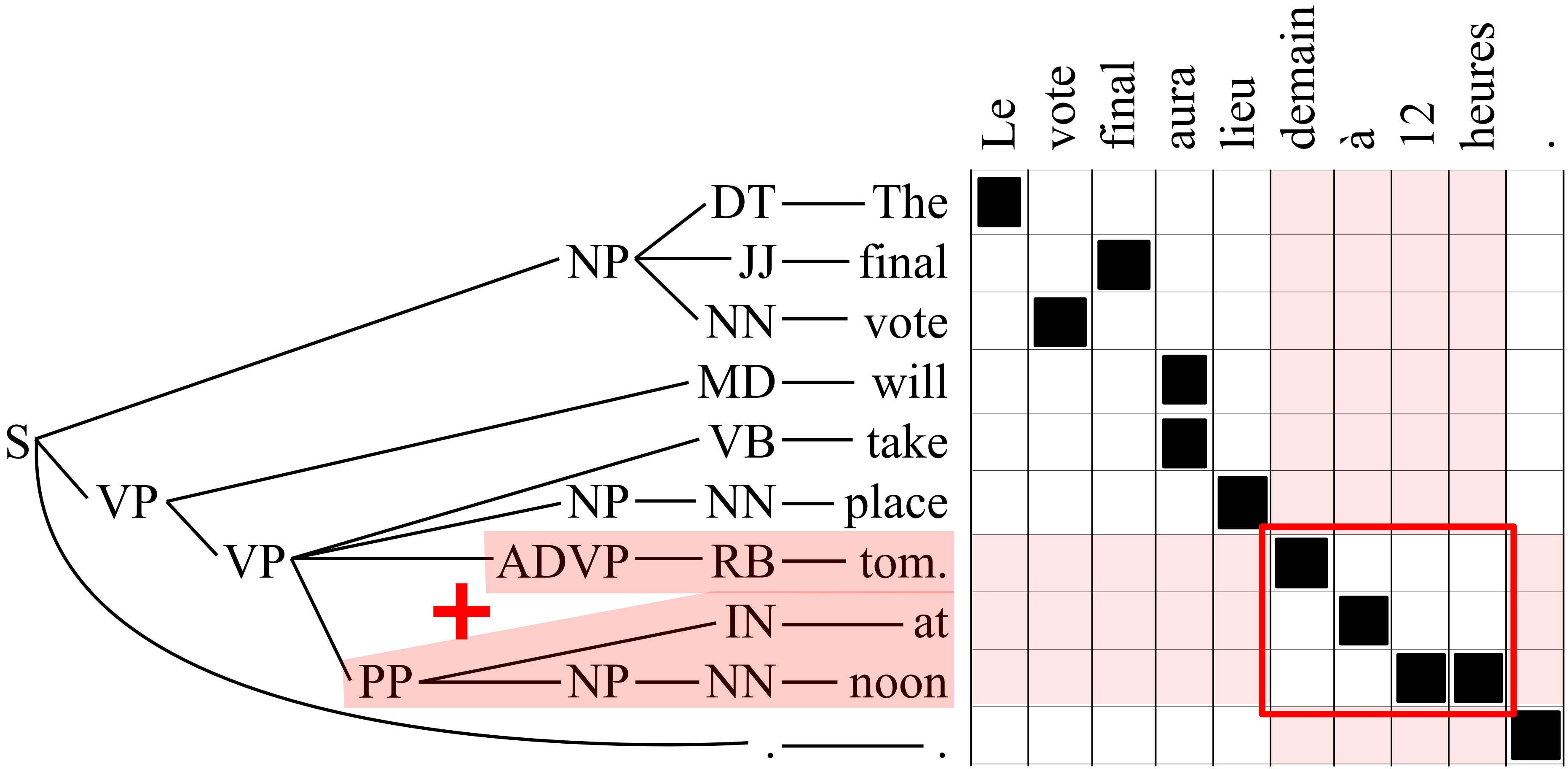


SAMT Rule Extraction



VP → [aura lieu demain à 12 heures]::[will take place tomorrow at noon]

SAMT Rule Extraction



VP → [aura lieu demain à 12 heures]::[will take place tomorrow at noon]

ADVP+PP → [demain à 12 heures]::[tomorrow at noon]

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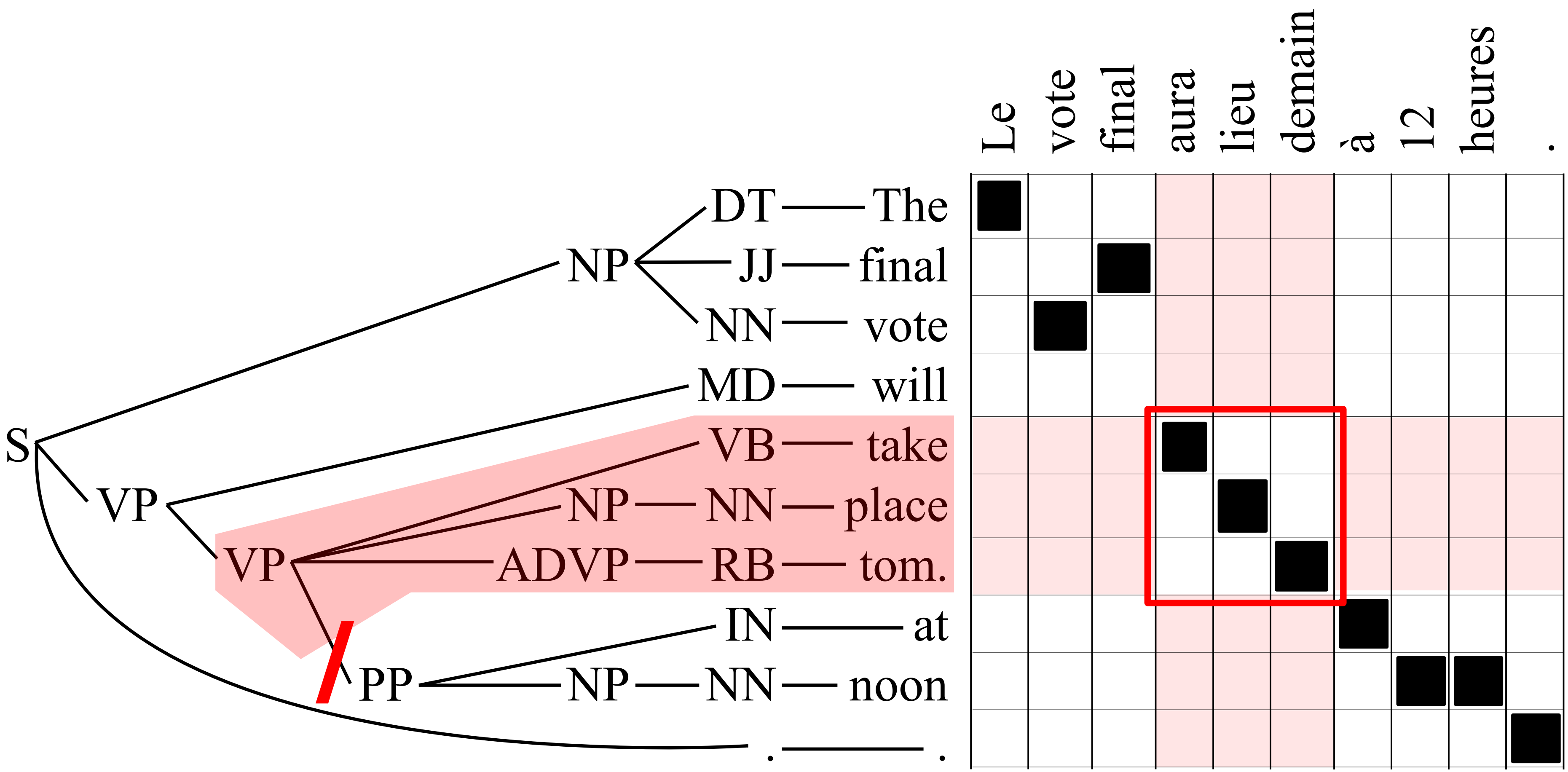
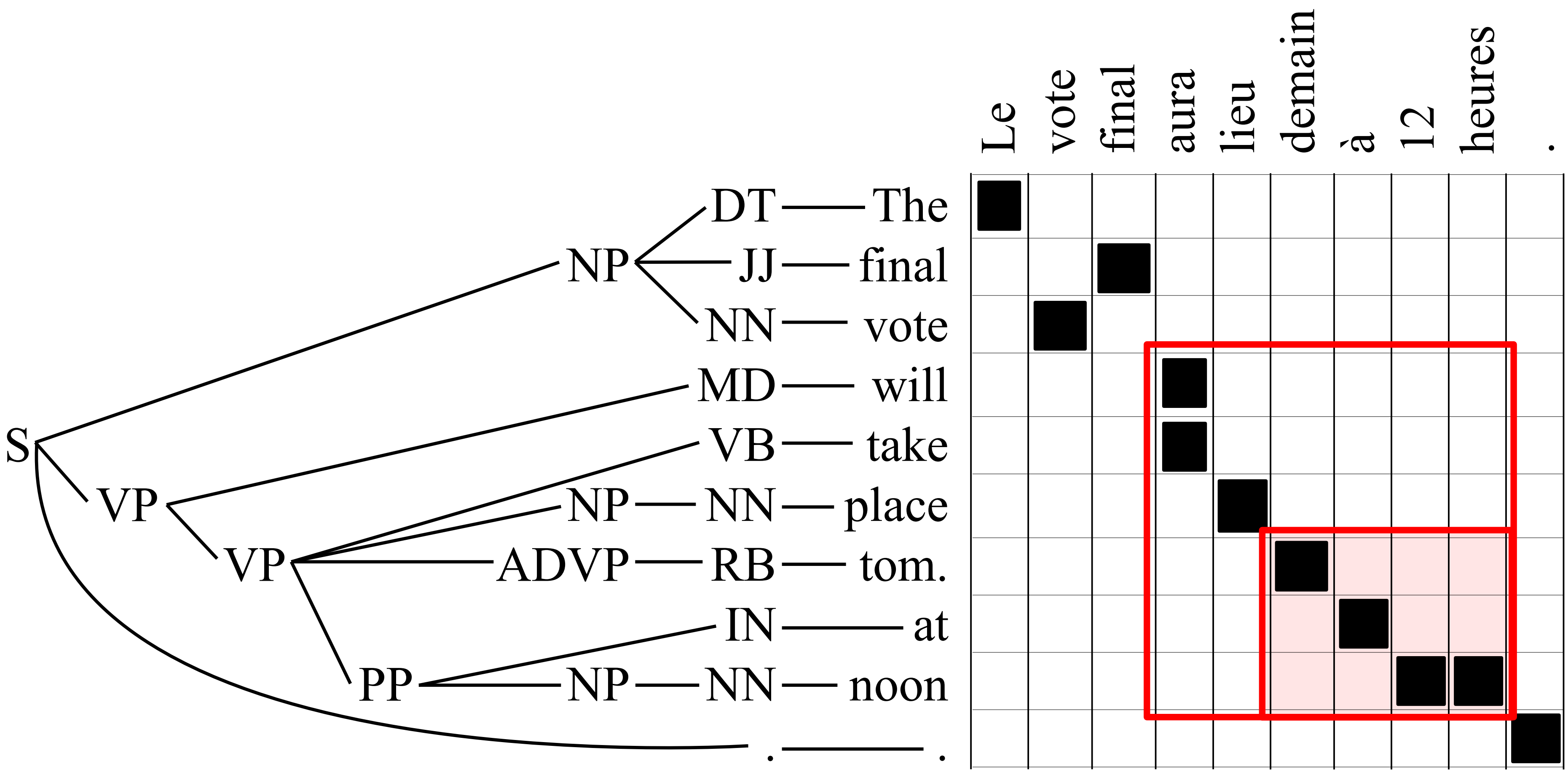


VP → [aura lieu demain à 12 heures]::[will take place tomorrow at noon]

ADVP+PP → [demain à 12 heures]::[tomorrow at noon]

VP/PP → [aura lieu demain]::[take place tomorrow]

SAMT Rule Extraction



VP → [aura lieu demain à 12 heures]::[will take place tomorrow at noon]

ADVP+PP → [demain à 12 heures]::[tomorrow at noon]

VP → [aura lieu ADVP+PP$_1$]::[will take place ADVP+PP$_1$]

SAMT Labeling

- Try, in order:
  - A exact constituent match
  - A+B adjacent constituents (not nec. siblings)
  - A/B partial A "missing a B to its right"
  - A\B partial A "missing a B to its left"
  - X if all else fails
- Slash labels are from combinatory categorial grammar
- About 4000 unique labels for English!

Translating with SAMT

$NNS \rightarrow$ [enfants]::[children]

$NP \rightarrow$ [J']::[I]

$S \rightarrow [NP_1\ S\backslash NP_2]::[NP_1\ S\backslash NP_2]$

$S \rightarrow [S_1\ SBAR_2\ .]::[S_1\ SBAR_2\ .]$

$S\backslash NP \rightarrow$ [aime les livres]::[like books]

$SBAR \rightarrow [\text{que } VBP_1 \text{ les } NNS_2]::[\text{that } NNS_2\ VBP_1]$

$SBAR \rightarrow [\text{que } S/NP_1 \text{ les } NNS_2]::[\text{that } S/NP_1 \text{ the } NNS_2]$

$VBP \rightarrow$ [lisent]::[read]

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S → [NP_1 $S\backslash NP_2$]::[NP_1 $S\backslash NP_2$]

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S\NP → [aime les livres]::[like books]

SBAR → [que VBP_1 les NNS_2]::[that NNS_2 VBP_1]

SBAR → [que S/NP_1 les NNS_2]::[that S/NP_1 the NNS_2]

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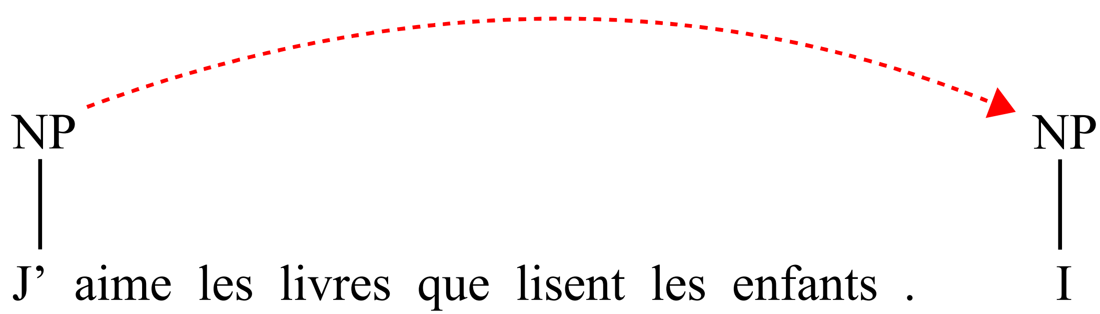

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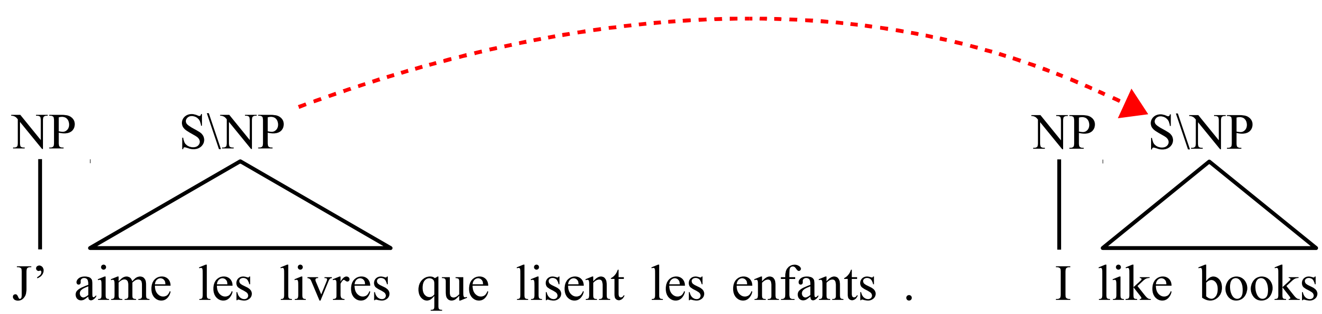

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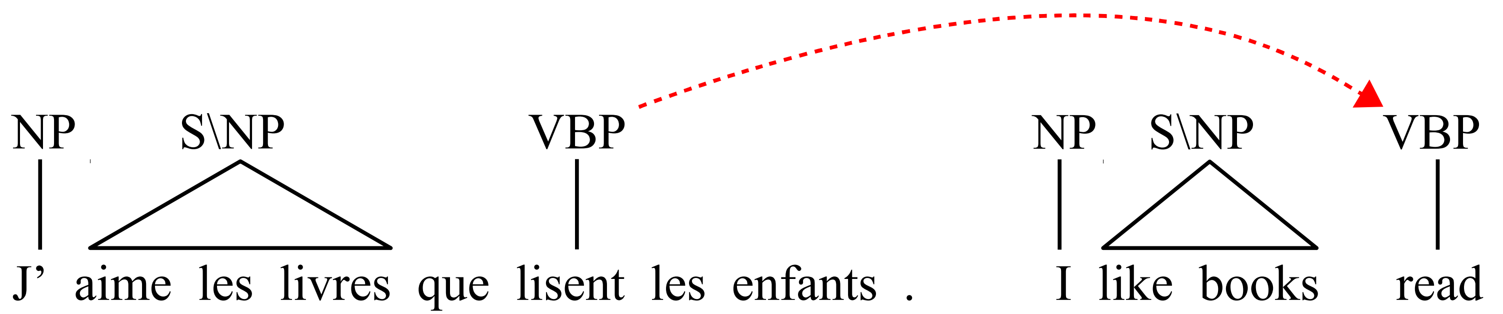

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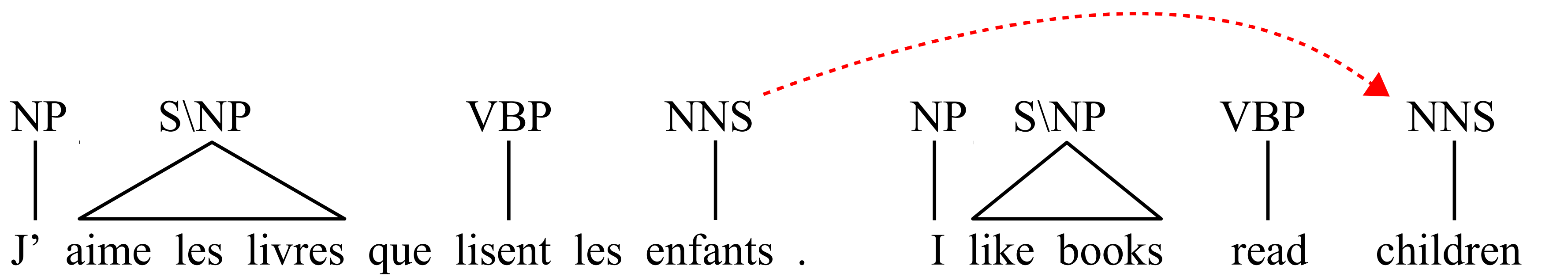

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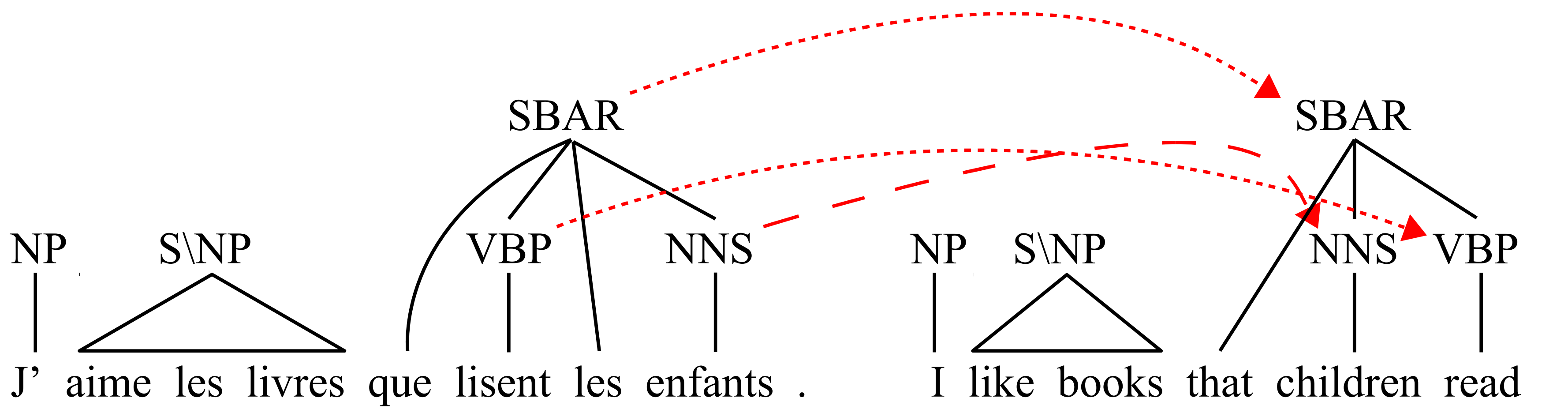

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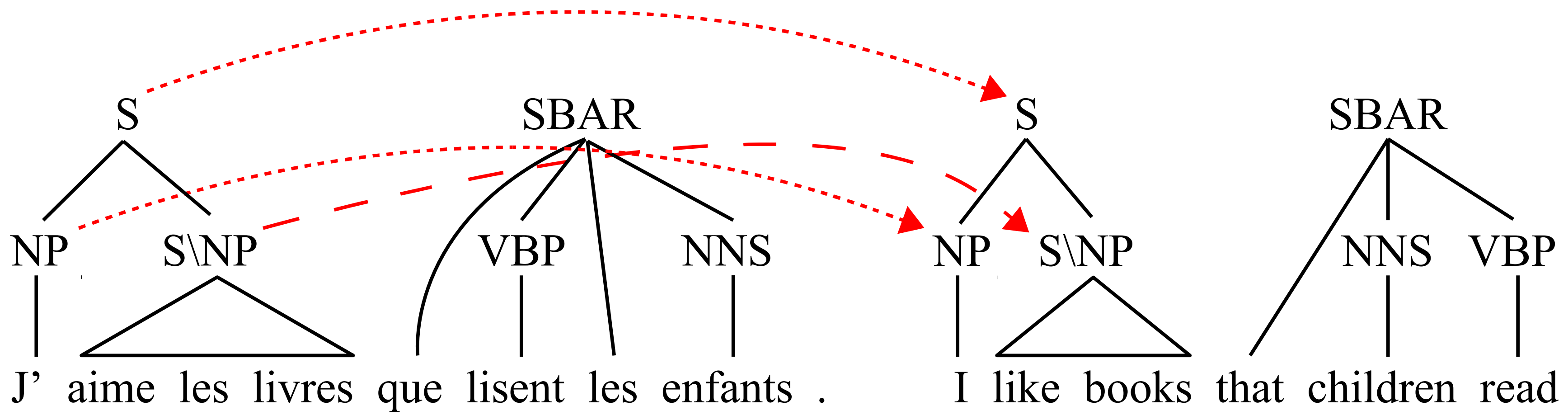

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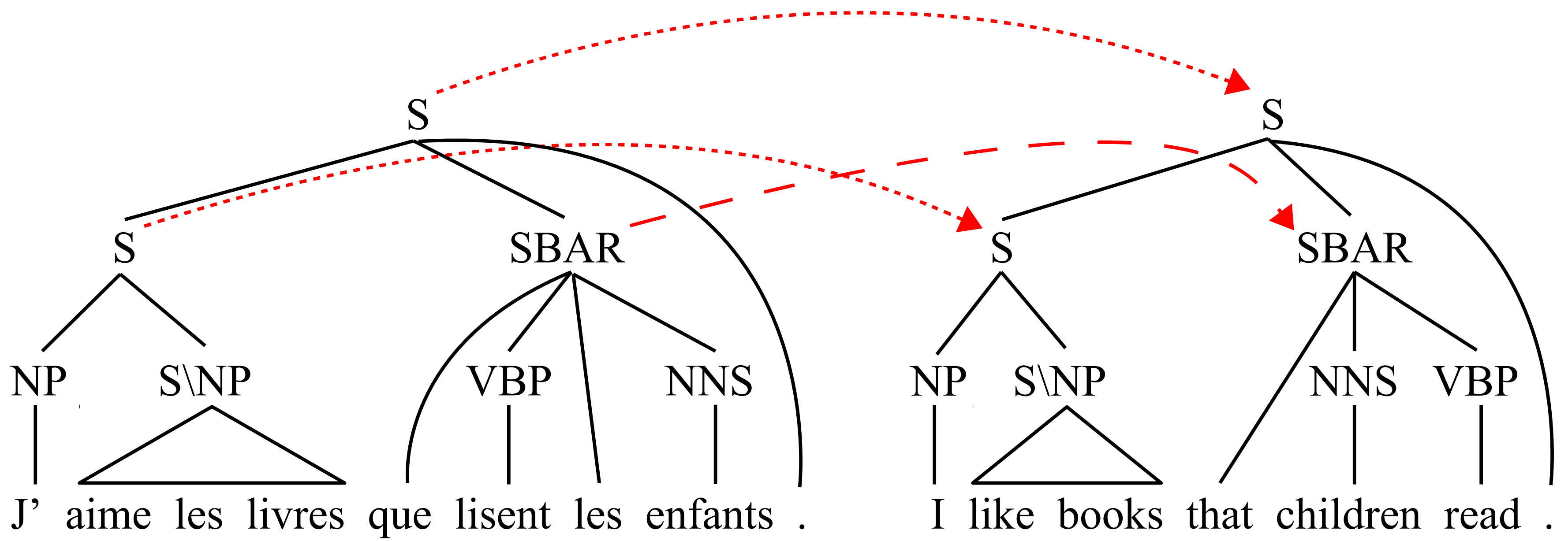

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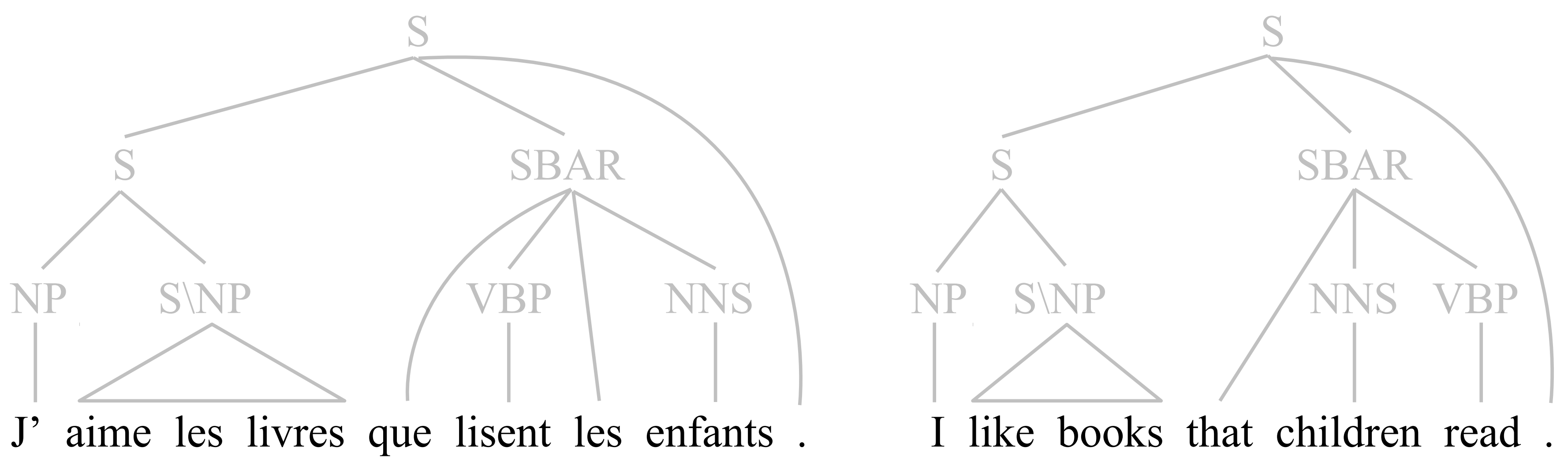

The Importance of Labels

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$\cancel{VBP} \rightarrow$ [lisent]::[read]

$VB \rightarrow$ [lisent]::[read]

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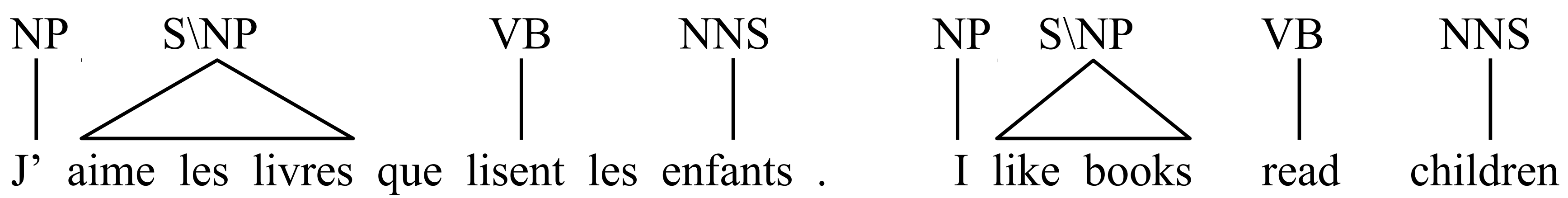

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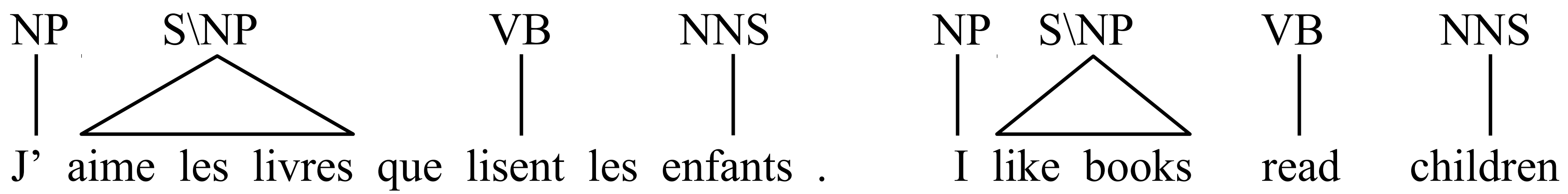
VB $\rightarrow$ [lisent]::[read]

VB ≠ VBP

No match!



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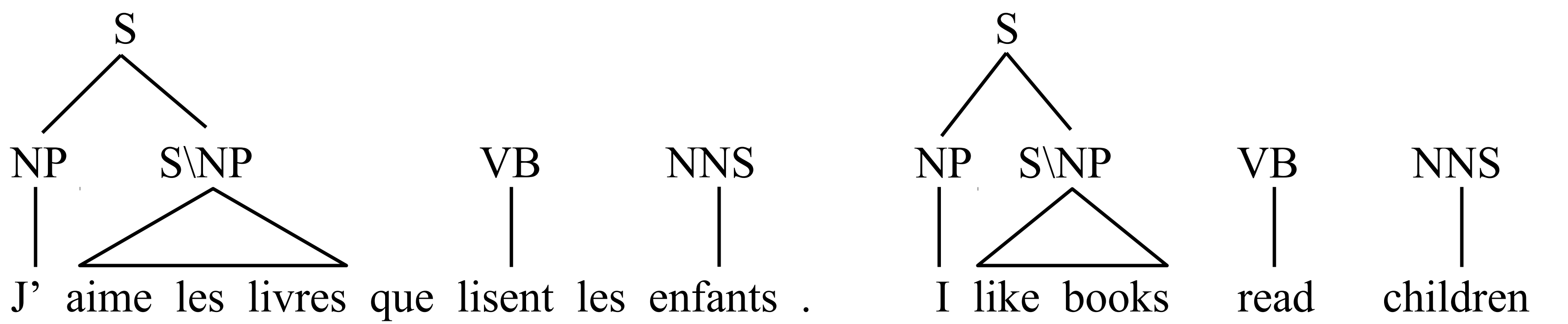
How do we finish parsing and translating?

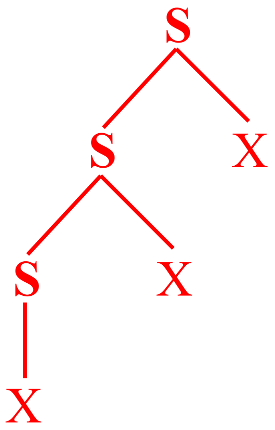


The Importance of Labels

- Label of constituent being parsed must exactly match right-hand side of rule
- If no match in grammar, need a fallback: **glue rules**
- Finish translation without "real" syntax

$$\mathbf{S} \rightarrow [X_1]::[X_1]$$

$$\mathbf{S} \rightarrow [\mathbf{S}_1\ X_2]::[\mathbf{S}_1\ X_2]$$



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$$\mathbf{S} \rightarrow [\mathbf{S}_1\ X_2]::[\mathbf{S}_1\ X_2]$$

$$\mathbf{S} \rightarrow [JJ{+}NN_1]::[JJ{+}NN_1]$$

$$\mathbf{S} \rightarrow [\mathbf{S}_1\ JJ{+}NN_2]::[\mathbf{S}_1\ JJ{+}NN_2]$$

$$\mathbf{S} \rightarrow [NP_1]::[NP_1]$$

$$\mathbf{S} \rightarrow [\mathbf{S}_1\ NP_2]::[\mathbf{S}_1\ NP_2]$$

$$\mathbf{S} \rightarrow [VP\backslash VBZ_1]::[VP\backslash VBZ_1]$$

$$\mathbf{S} \rightarrow [\mathbf{S}_1\ VP\backslash VBZ_2]::[\mathbf{S}_1\ VP\backslash VBZ_2]$$

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- Label of constituent being parsed must exactly match right-hand side of rule
- If no match in grammar, need a fallback: **glue rules**
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$\mathbf{S} \rightarrow [X_1]::[X_1]$ … $]::[JJ{+}NN_1]$

$\mathbf{S} \rightarrow [\mathbf{S}_1\ X_2]::[\mathbf{S}$ … $]::[\mathbf{S}_1\ JJ{+}NN_2]$

$\mathbf{S} \rightarrow [NP_1]::[N$ … $Z_1]::[VP\backslash VBZ_1]$

$\mathbf{S} \rightarrow [\mathbf{S}_1\ NP_2]::[\mathbf{S}_1\ N$ … $_2]$ … $[\mathbf{S}_1\ VP\backslash VBZ_2]::[\mathbf{S}_1\ VP\backslash VBZ_2]$

One pair for each nonterminal in the grammar!

Translating with Glue Rules

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NP → [J']::[I]

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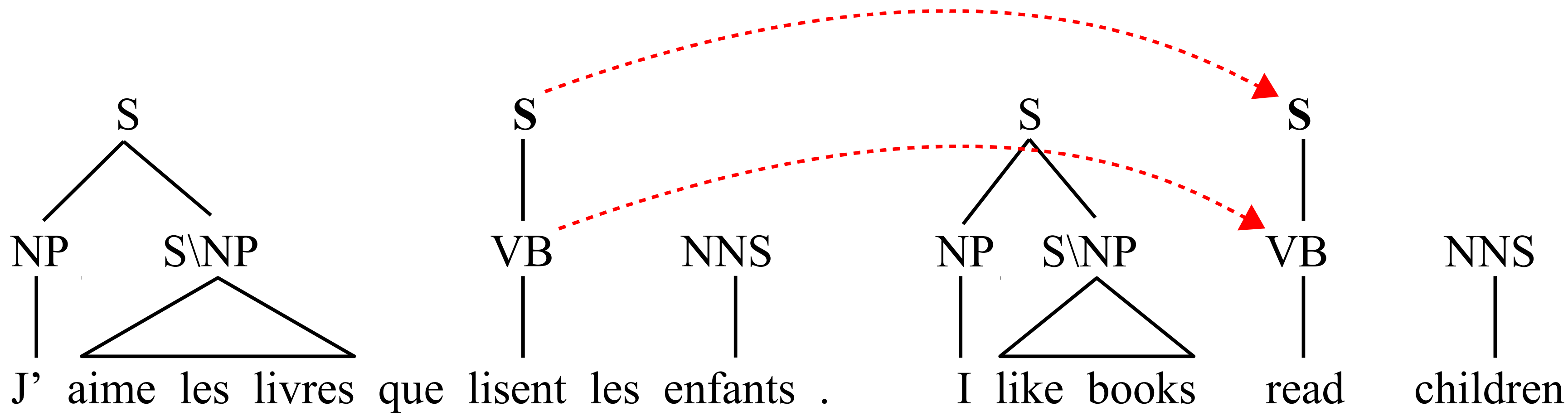
$SBAR \rightarrow [\text{que } S/NP_1 \text{ les } NNS_2]::[\text{that } S/NP_1 \text{ the } NNS_2]$

VB → [lisent]::[read]

$\mathbf{S} \rightarrow [VB_1]::[VB_1]$



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S → [S$_1$ SBAR$_2$.]::[S$_1$ SBAR$_2$.]

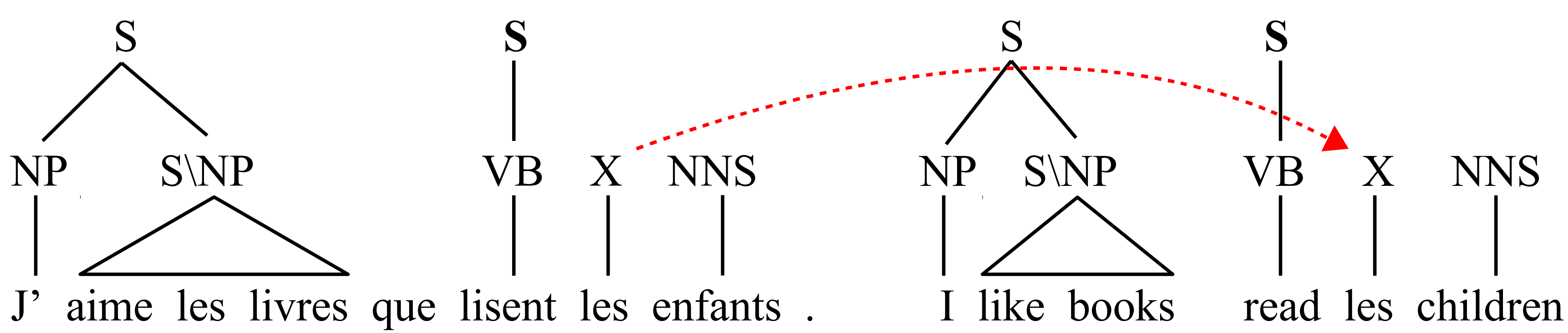
S\NP → [aime les livres]::[like books]

SBAR → [que VBP$_1$ les NNS$_2$]::[that NNS$_2$ VBP$_1$]

SBAR → [que S/NP$_1$ les NNS$_2$]::[that S/NP$_1$ the NNS$_2$]

VB → [lisent]::[read]

X → [les]::[les]



Translating with Glue Rules

NNS → [enfants]::[children]

NP → [J']::[I]

S → [NP_1 $S\backslash NP_2$]::[NP_1 $S\backslash NP_2$]

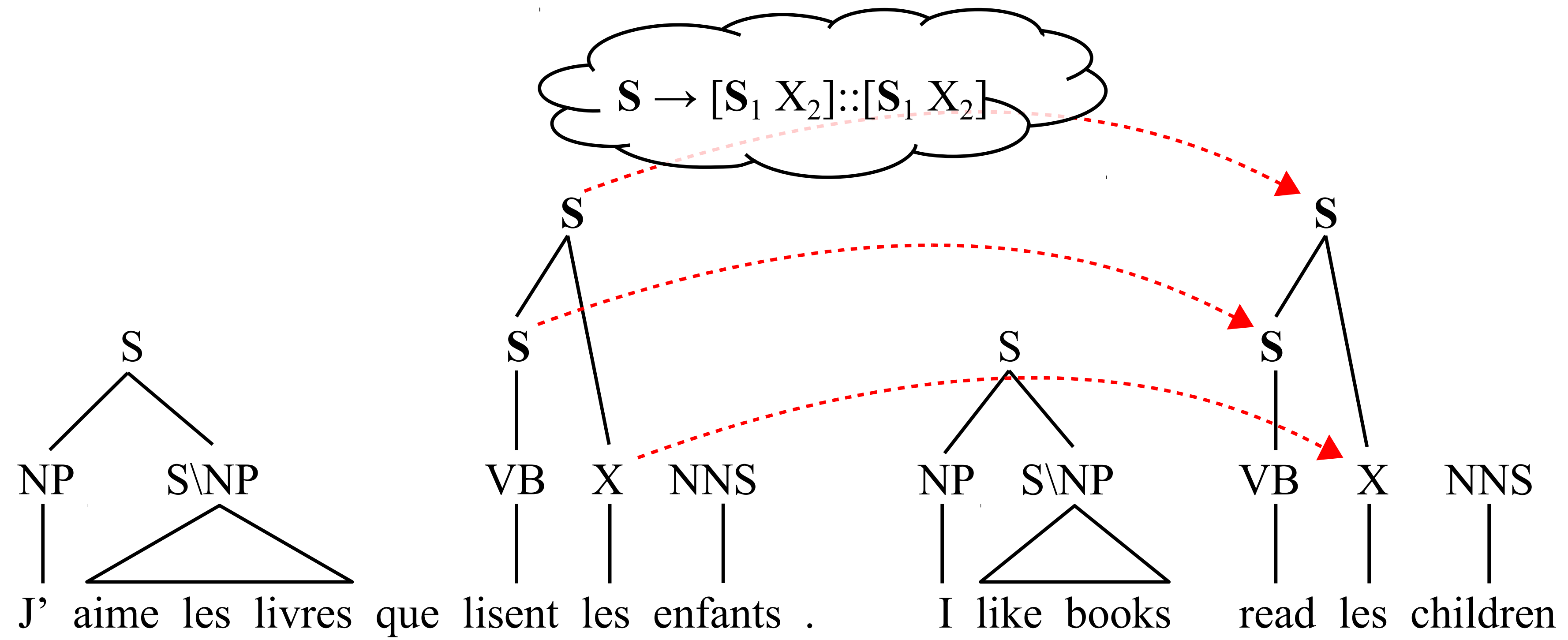
S → [S_1 $SBAR_2$.]::[S_1 $SBAR_2$.]

S\NP → [aime les livres]::[like books]

SBAR → [que VBP_1 les NNS_2]::[that NNS_2 VBP_1]

SBAR → [que S/NP_1 les NNS_2]::[that S/NP_1 the NNS_2]

VB → [lisent]::[read]



Translating with Glue Rules

$NNS \rightarrow [\text{enfants}]::[\text{children}]$

$NP \rightarrow [\text{J'}]::[\text{I}]$

$S \rightarrow [NP_1\ S\backslash NP_2]::[NP_1\ S\backslash NP_2]$

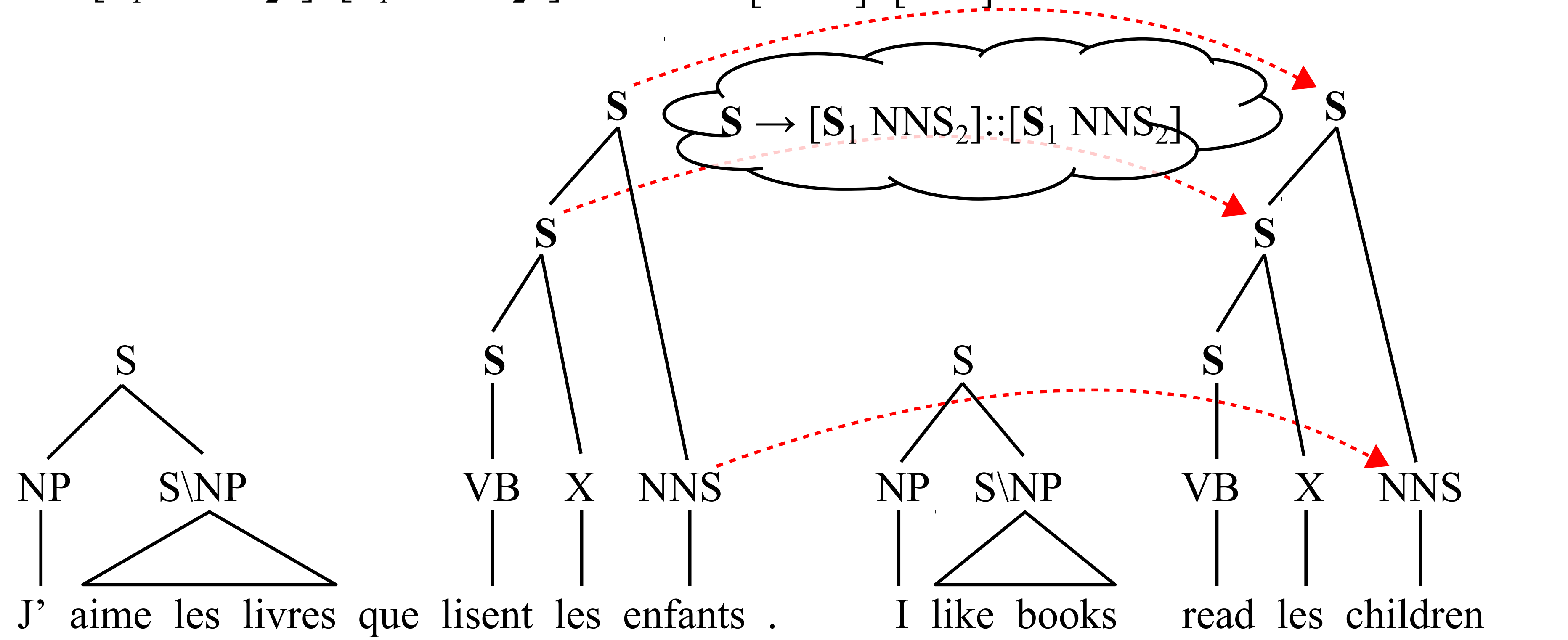
$S \rightarrow [S_1\ SBAR_2\ .]::[S_1\ SBAR_2\ .]$

$S\backslash NP \rightarrow [\text{aime les livres}]::[\text{like books}]$

$SBAR \rightarrow [\text{que}\ VBP_1\ \text{les}\ NNS_2]::[\text{that}\ NNS_2\ VBP_1]$

$SBAR \rightarrow [\text{que}\ S/NP_1\ \text{les}\ NNS_2]::[\text{that}\ S/NP_1\ \text{the}\ NNS_2]$

VB $\rightarrow$ [lisent]::[read]



SAMT Summary

- Label Hiero rules with nonterminals derived from parse trees
- Decisions made:
  - Syntax on: Target side
  - Rule formalism: SCFG
  - Input: String
  - Label space: Treebank + combinations
- Extensions: Venugopal et al. [2009], Chiang [2010], Zollmann [2011]

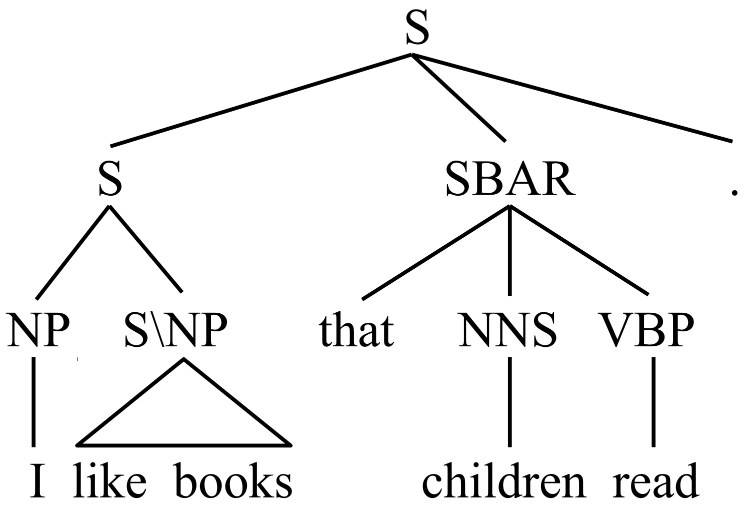
SAMT Pros and Cons

SAMT Pros and Cons

- No coverage loss from phrase-based MT
- Distinguishes different syntactic contexts

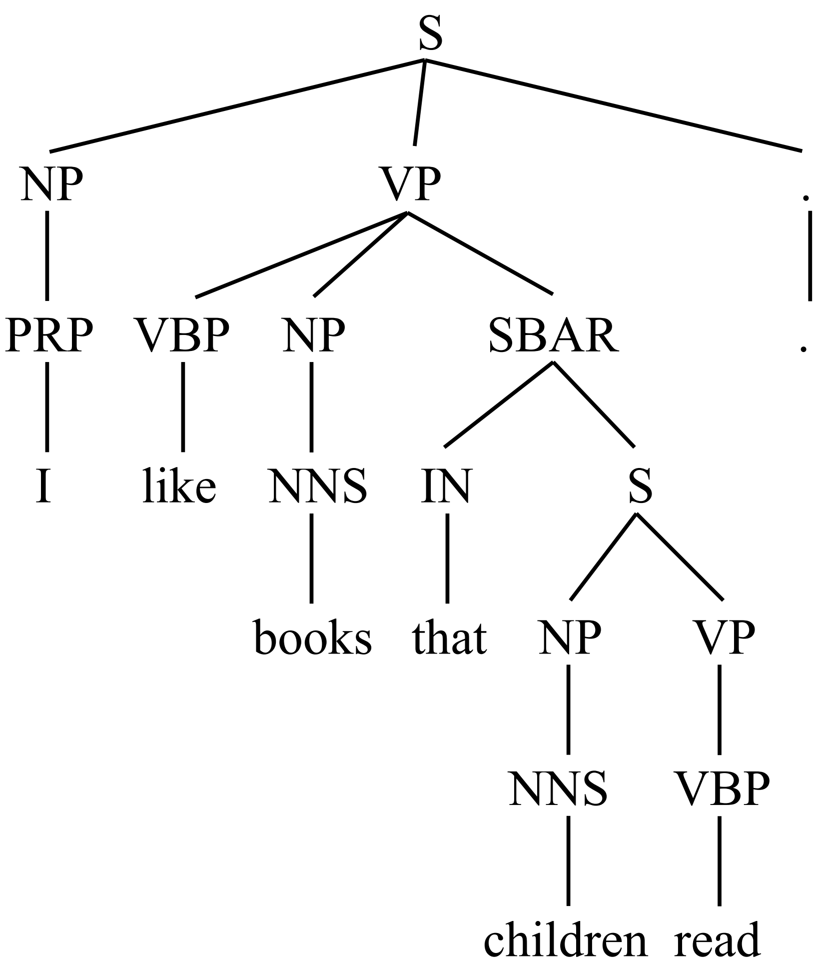
- Very large label set = sparse rules
- Still may need to restrict rule shape (Hiero)
- Produces weird tree structure

SAMT vs. “Native” Trees

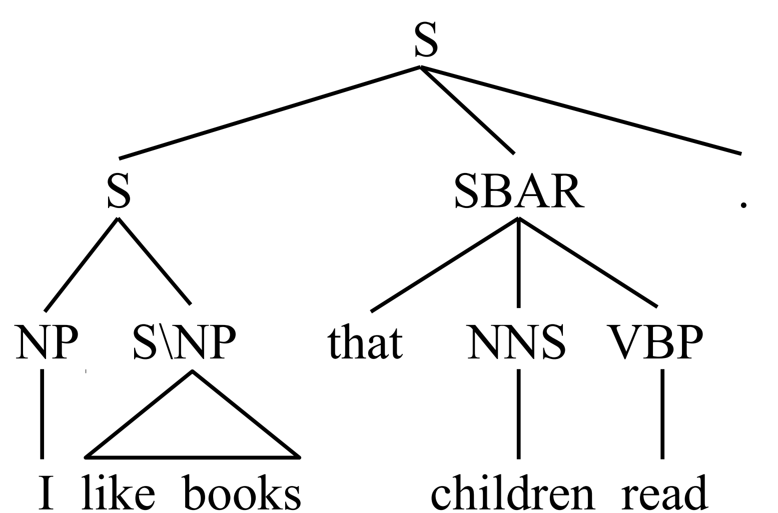


SAMT vs. "Native" Trees

Stanford Parser



SAMT decoding



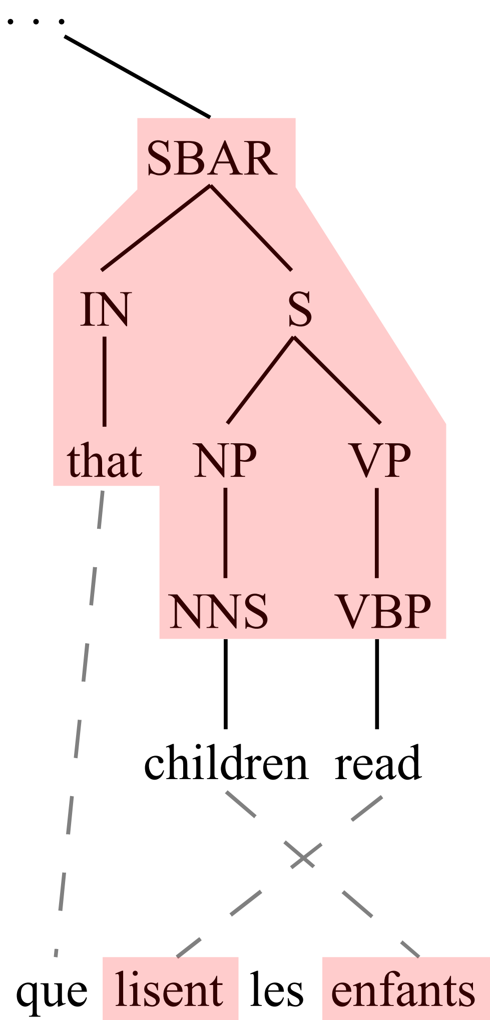
Galley, Hopkins, Knight, Marcu

[Galley et al., 2004; Galley et al., 2006]

- Let’s use larger fragments of tree structure!
- Keep internal nodes in the rule
- Require exact constituent match, but relax Hiero/SAMT rule format constraints
- Needs generalization of SCFG: tree-to-string transducer rules (“xRs”) or synchronous tree-substitution grammar

Galley, Hopkins, Knight, Marcu

[Galley et al., 2004; Galley et al., 2006]

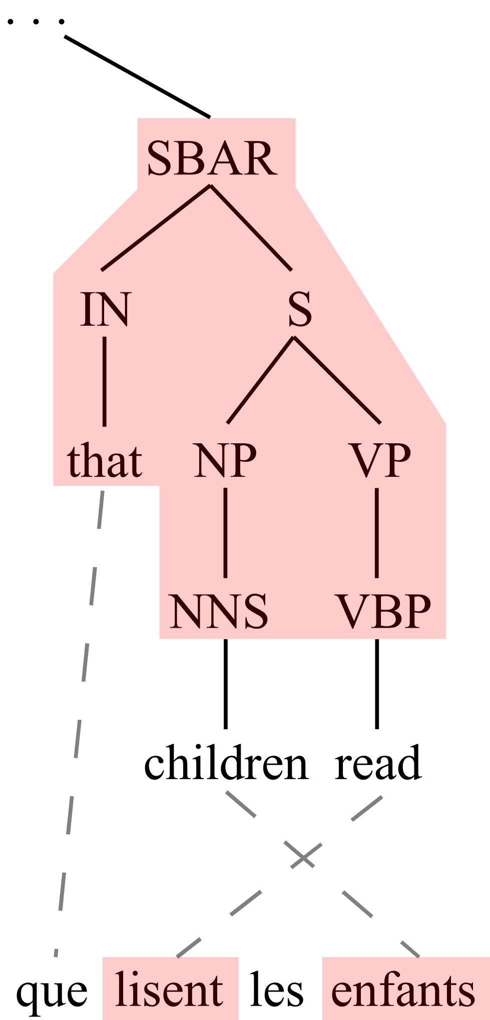


Extracted SAMT rule (SCFG)

$$\text{SBAR} \rightarrow [\text{que VBP}_1 \text{ les NNS}_2]::$$
$$[\text{that NNS}_2 \text{ VBP}_1]$$

Galley, Hopkins, Knight, Marcu

[Galley et al., 2004; Galley et al., 2006]



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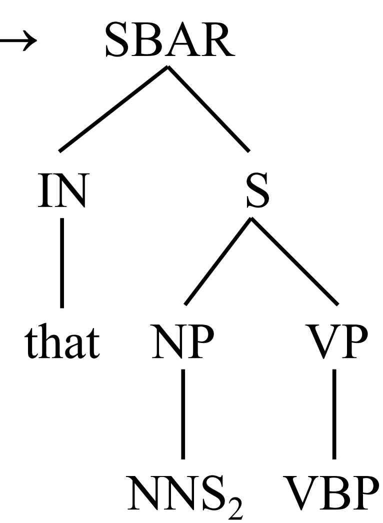
$$\text{SBAR} \rightarrow [\text{que VBP}_1 \text{ les NNS}_2] :: [\text{that NNS}_2 \text{ VBP}_1]$$

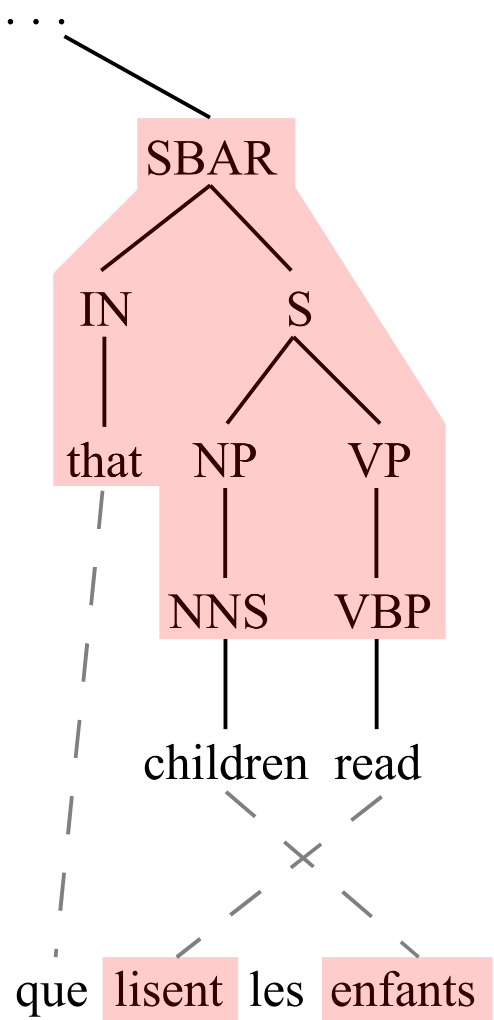
Extracted GHKM rule (xRs)

que VBP_1 les NNS_2 $\rightarrow$



Galley, Hopkins, Knight, Marcu

[Galley et al., 2004; Galley et al., 2006]



Extracted SAMT rule (SCFG)

$$\text{SBAR} \rightarrow [\text{que VBP}_1 \text{ les NNS}_2]:: [\text{that NNS}_2 \text{ VBP}_1]$$

Extracted GHKM rule (xRs)

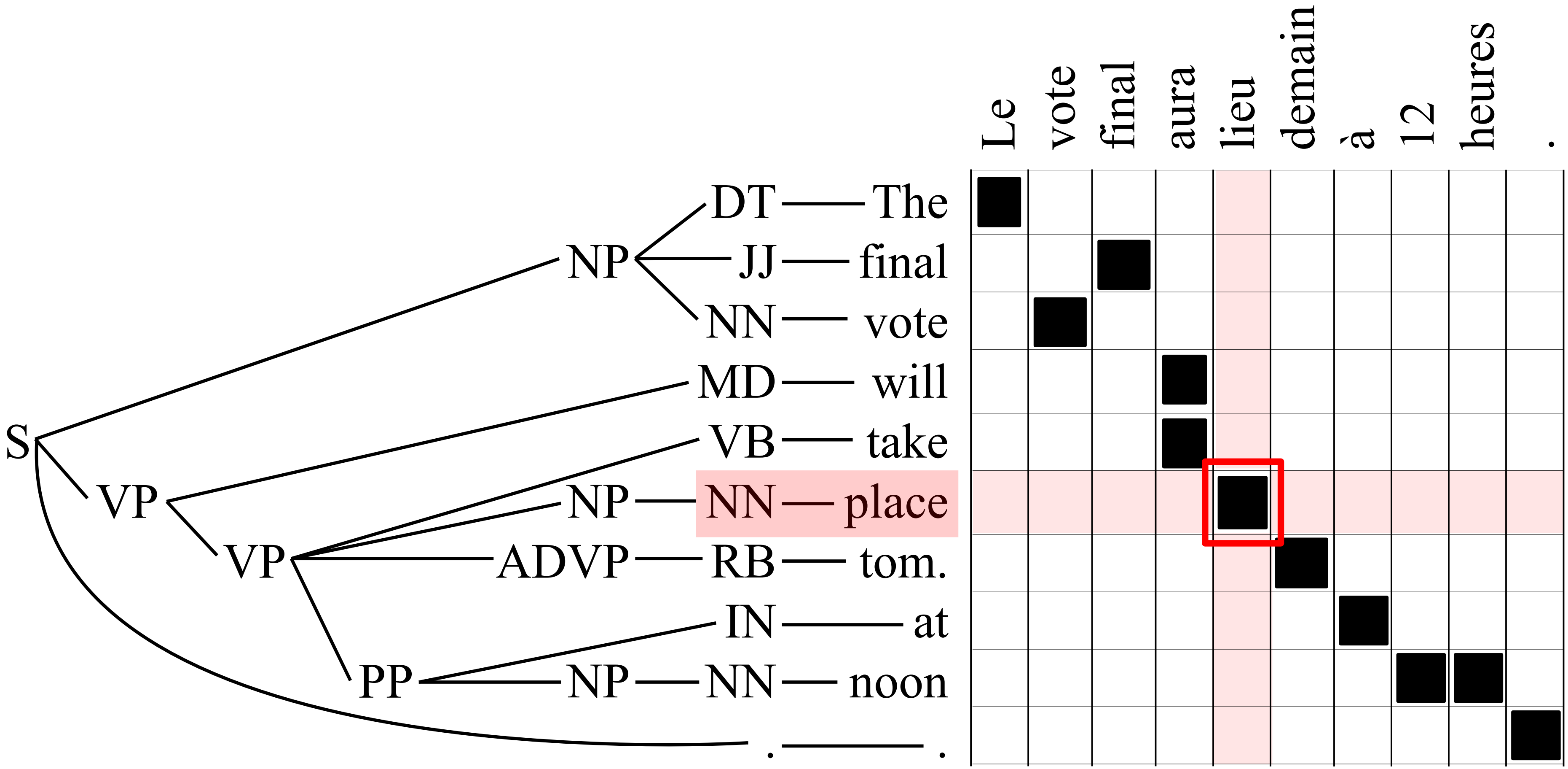
$$\text{que VBP}_1 \text{ les NNS}_2 \rightarrow \text{SBAR(IN(that) S(NP(NNS}_2\text{) VP(VBP}_1\text{)))}$$

Galley, Hopkins, Knight, Marcu

[Galley et al., 2004; Galley et al., 2006]

- Two extraction methods:
  - Minimal: break tree apart into smallest possible fragments
  - Composed: combine minimal fragments into larger ones that might overlap
- What about phrases that aren't constituents? Do we lose coverage?

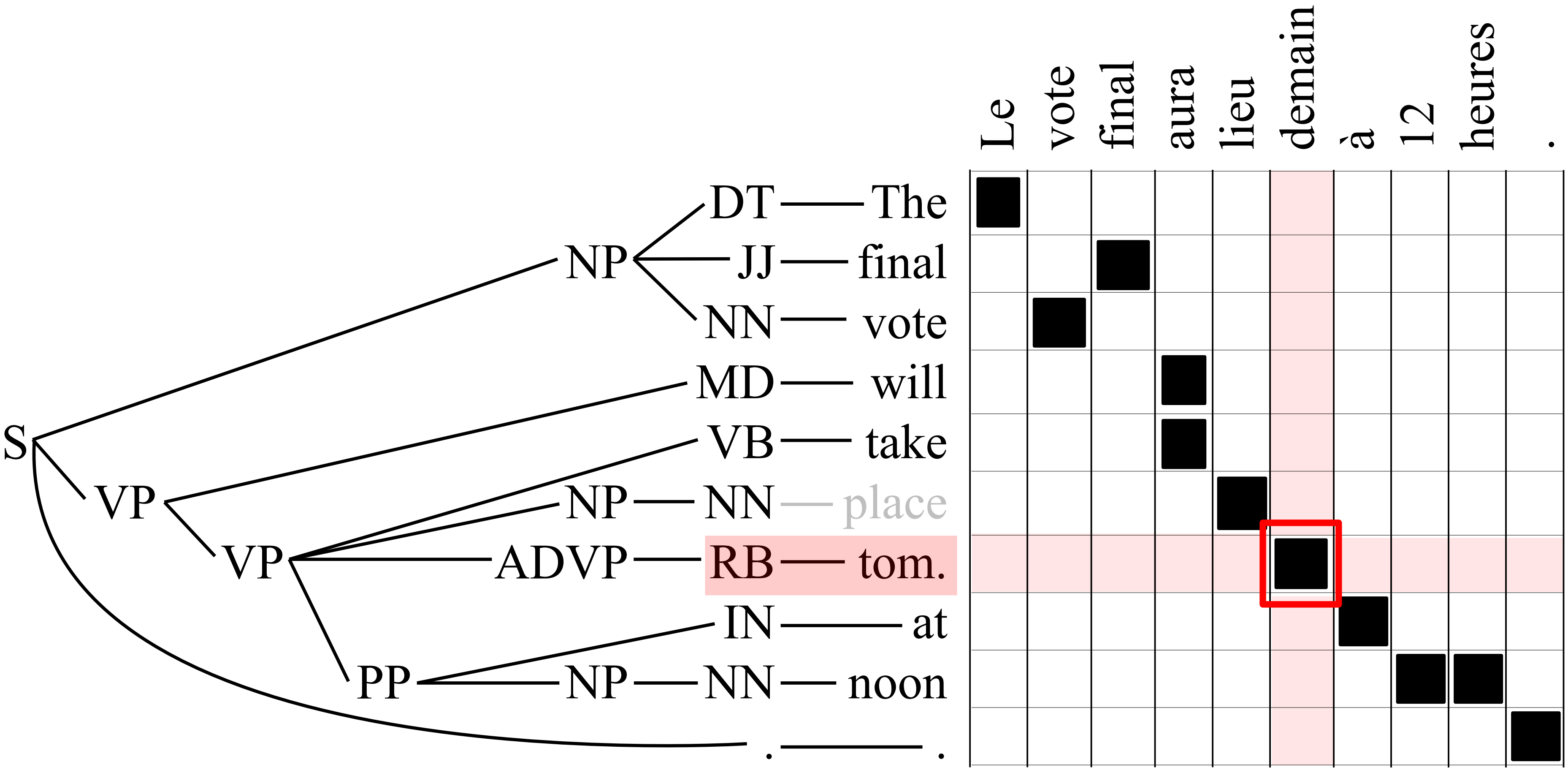
GHKM Minimal Rule Extraction



lieu → NN(place)

NN → [lieu]::[place]

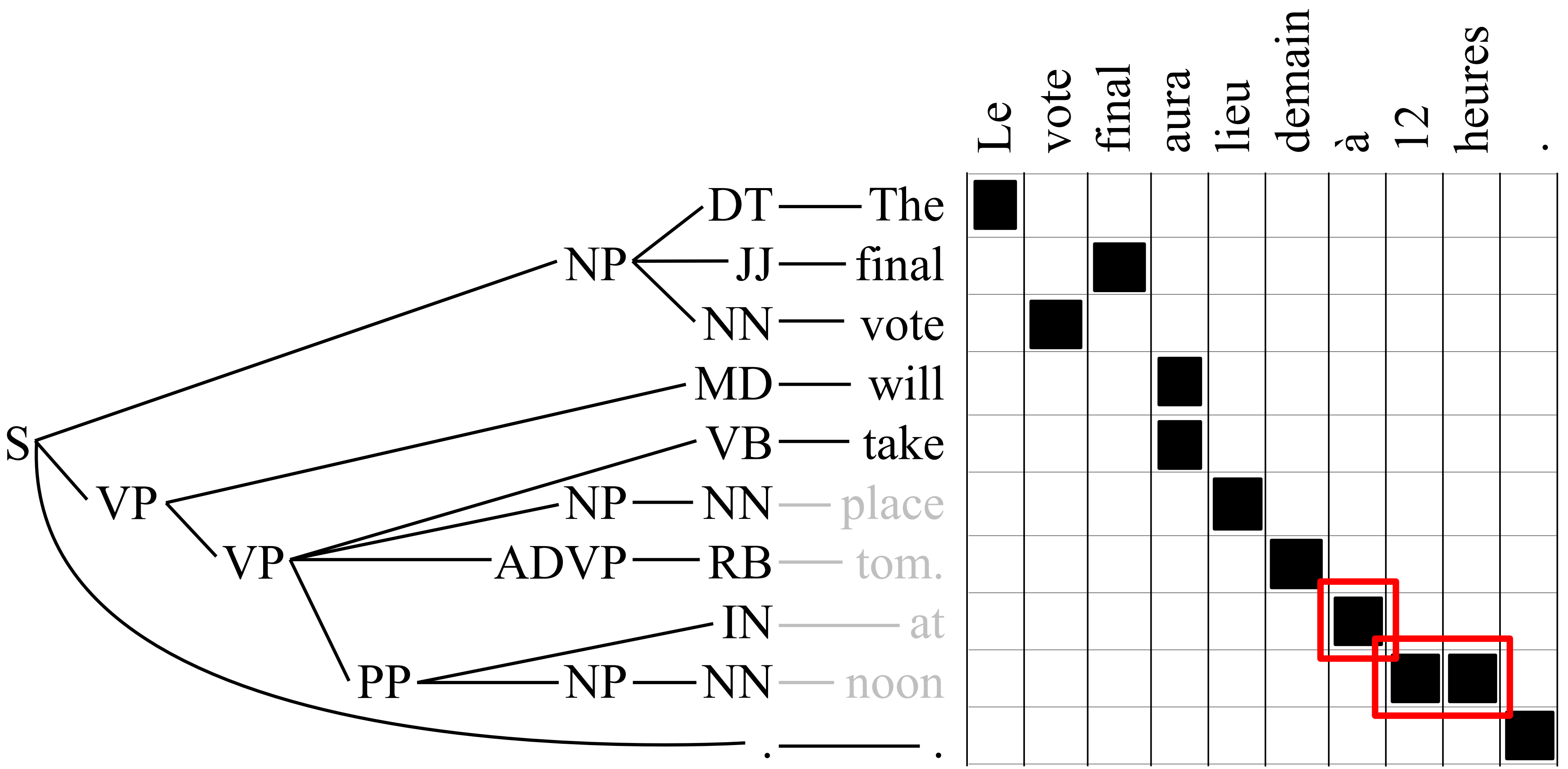
GHKM Minimal Rule Extraction



lieu → NN(place)

demain → RB(tomorrow)

GHKM Minimal Rule Extraction



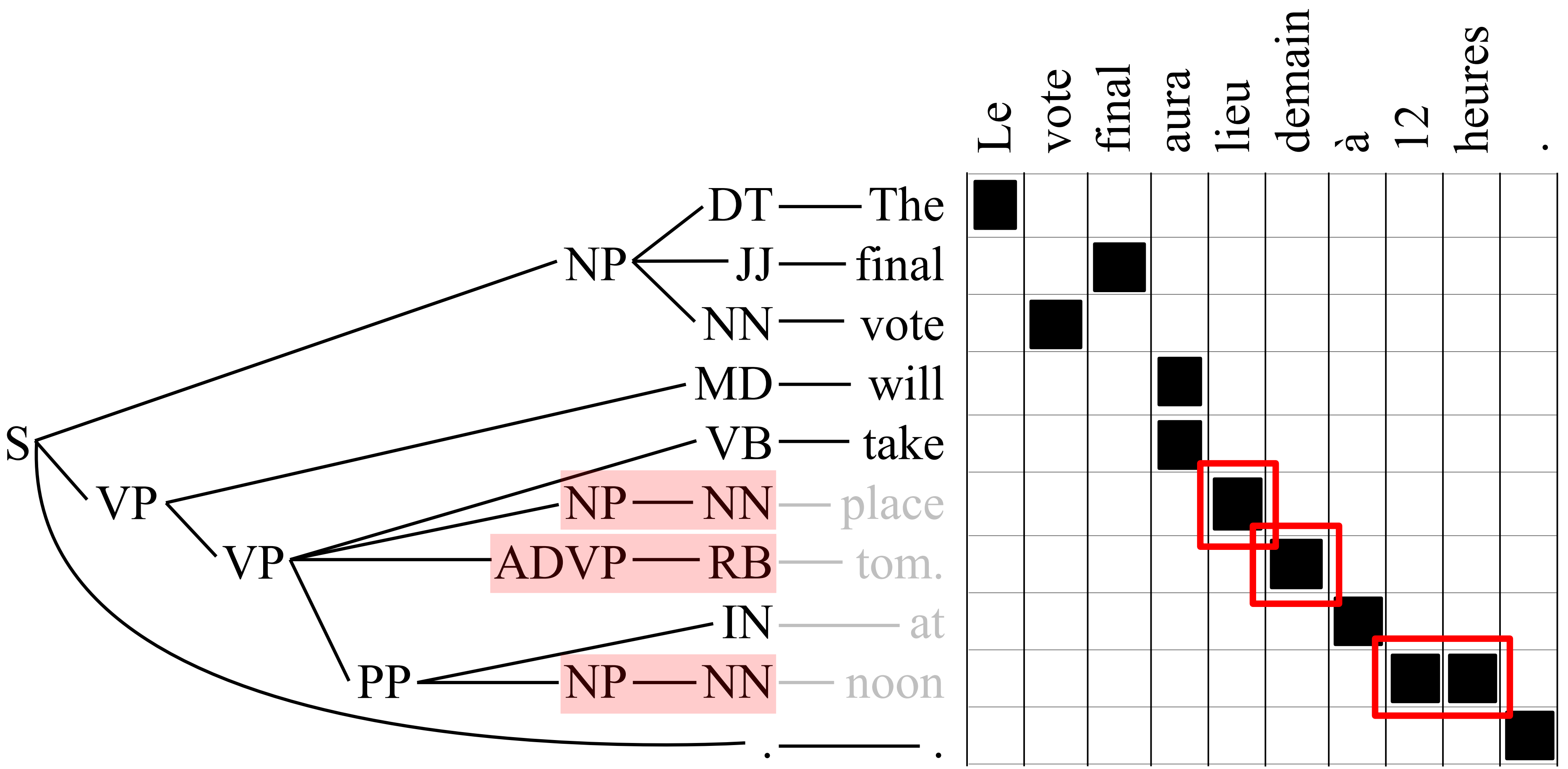
lieu → NN(place)

demain → RB(tomorrow)

à → IN(at)

12 heures → NN(noon)

GHKM Minimal Rule Extraction



lieu → NN(place)

demain → RB(tomorrow)

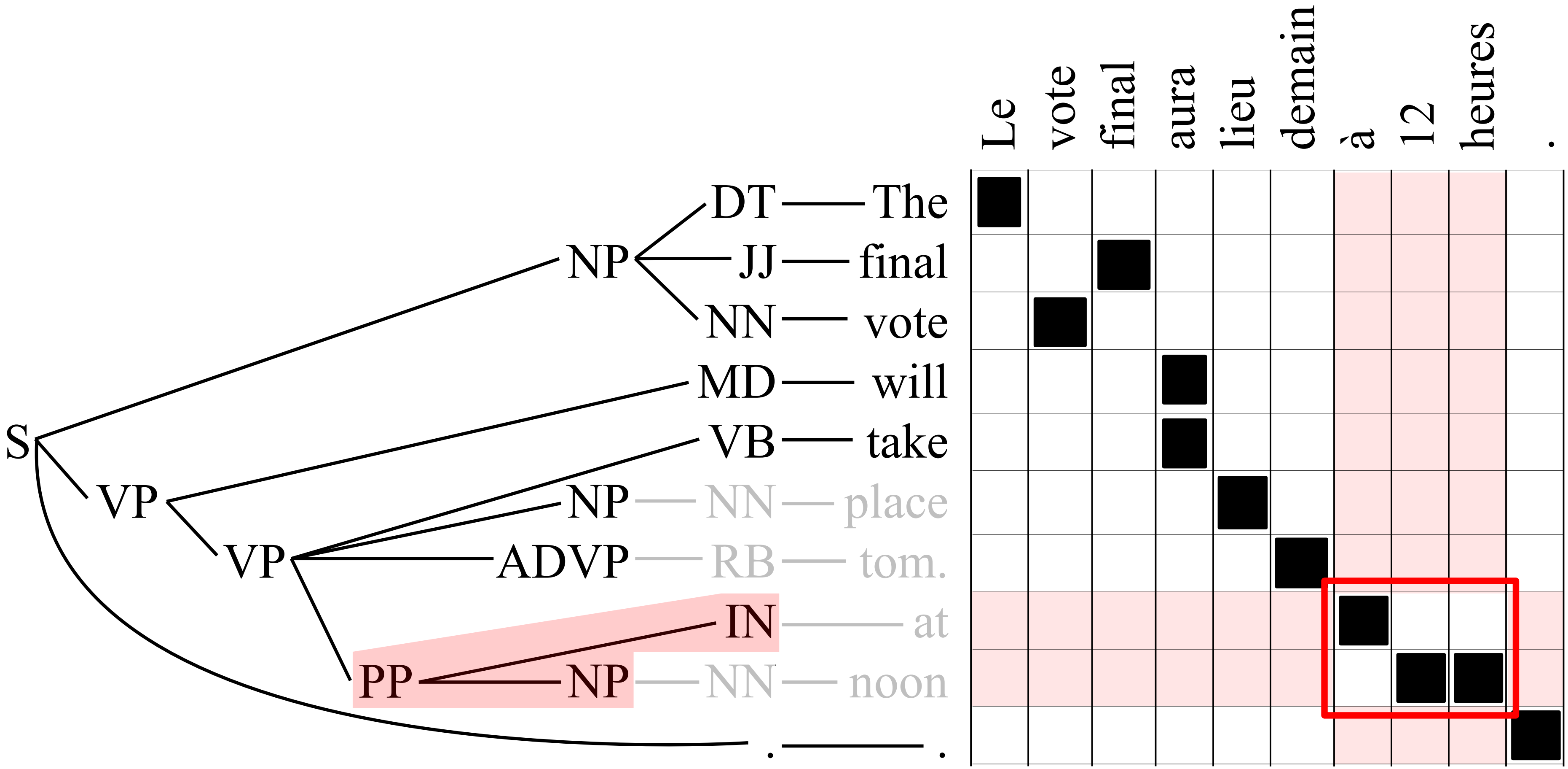
à → IN(at)

12 heures → NN(noon)

$NN_1 \rightarrow NP(NN_1)$ x2

$RB_1 \rightarrow ADVP(RB_1)$

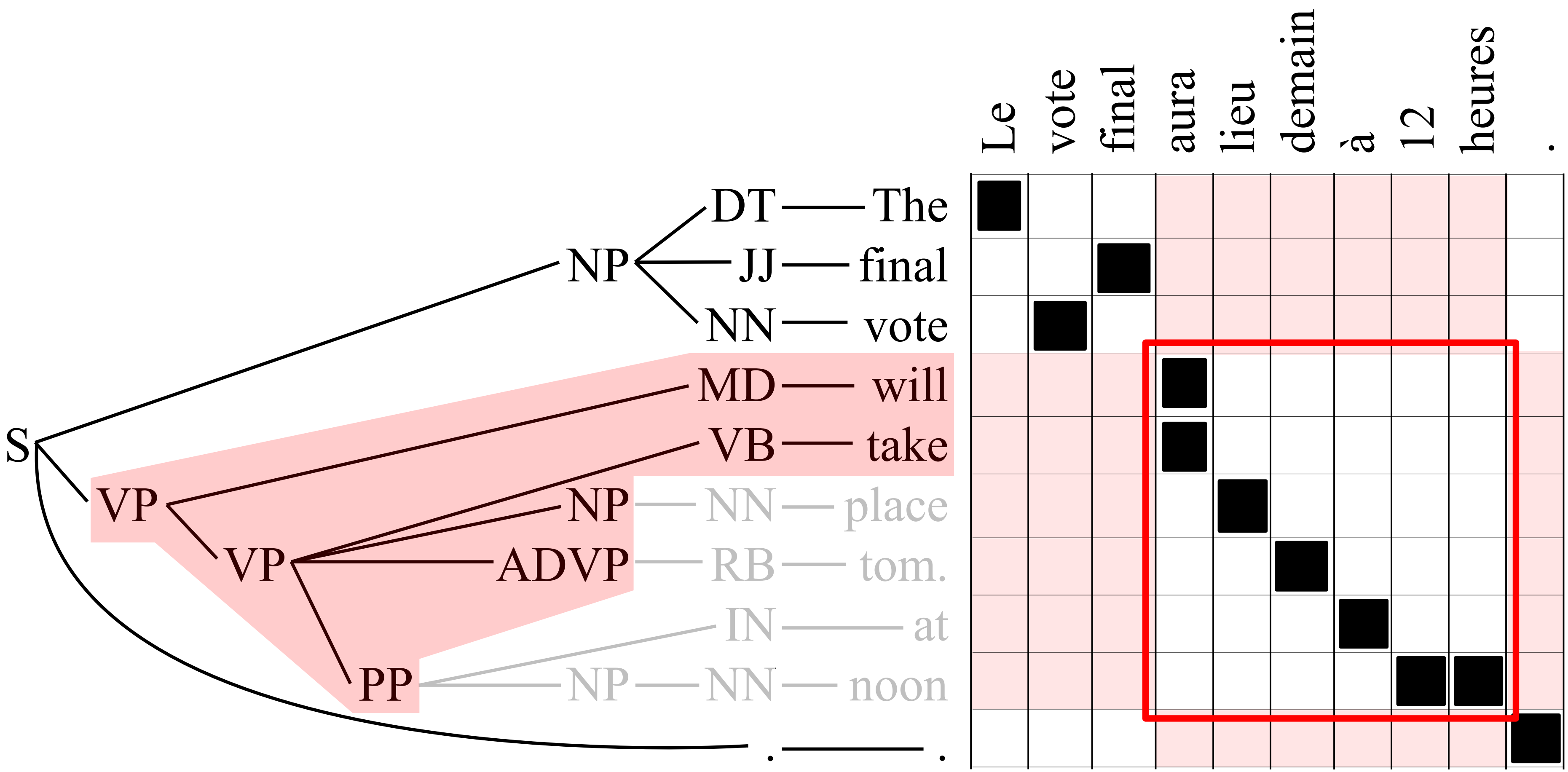
GHKM Minimal Rule Extraction



$\mathrm{IN}_1\ \mathrm{NP}_2 \rightarrow \mathrm{PP}(\mathrm{IN}_1\ \mathrm{NP}_2)$

$\mathrm{PP} \rightarrow [\mathrm{IN}_1\ \mathrm{NP}_2]::[\mathrm{IN}_1\ \mathrm{NP}_2]$

GHKM Minimal Rule Extraction

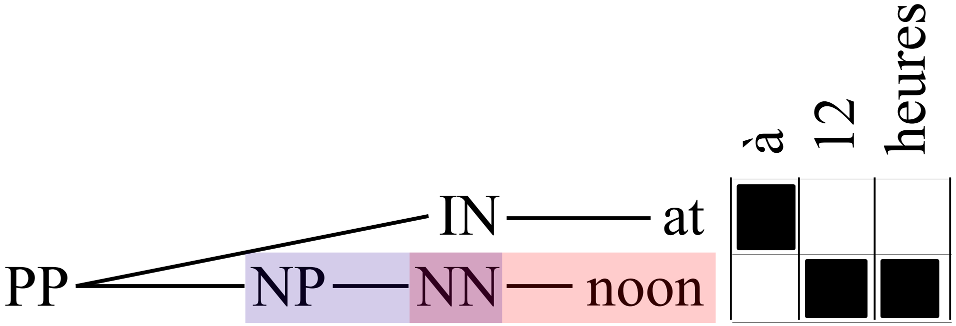


$IN_1\ NP_2 \rightarrow PP(IN_1\ NP_2)$

aura $NP_1\ ADVP_2\ PP_3 \rightarrow VP(MD(will)\ VP(VB(take)\ NP_1\ ADVP_2\ PP_3))$

GHKM Composed Rules

- When extracting minimal rules from a tree, plug two or more of them together



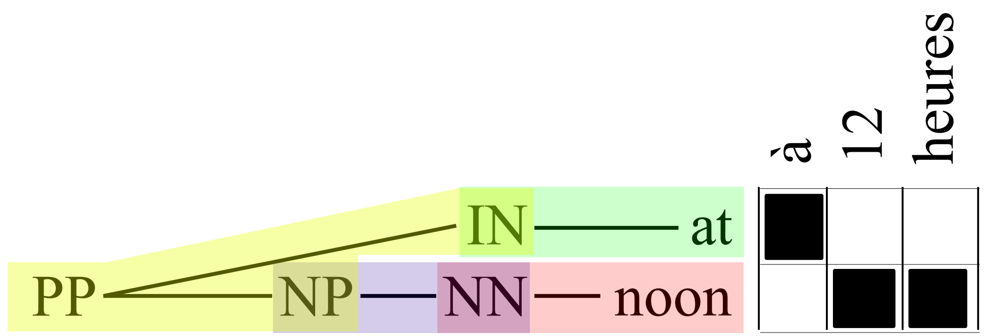
$$12 \text{ heures} \rightarrow \mathrm{NN}(\text{noon})$$

$$+ \quad \mathrm{NN}_1 \rightarrow \mathrm{NP}(\mathrm{NN}_1)$$

$$12 \text{ heures} \rightarrow \mathrm{NP}(\mathrm{NN}(\text{noon}))$$

GHKM Composed Rules

- When extracting minimal rules from a tree, plug two or more of them together



$$\text{12 heures} \rightarrow \text{NN(noon)}$$

$$\text{NN}_1 \rightarrow \text{NP}(\text{NN}_1)$$

$$\text{à} \rightarrow \text{IN(at)}$$

$$+ \quad \text{IN}_1\ \text{NP}_2 \rightarrow \text{PP}(\text{IN}_1\ \text{NP}_2)$$

$$\text{à 12 heures} \rightarrow \text{PP(IN(at) NP(NN(noon)))}$$

Consider the Following

- Where do unaligned words go?

- What happens at the top of the tree for a very long/flat sentence?

- Is the decomposition of the tree unique?

Consider the Following

- Where do unaligned words go?
  - Minimal: Attach at highest-level rule by fiat
  - Composed: Try attaching to all rules
- What happens at the top of the tree for a very long/flat sentence?
  - You get a very long (and likely sparse) S rule
- Is the decomposition of the tree unique?
  - Minimal: Yes, given unaligned words fiat
  - Composed: Definitely not!

Translating with GHKM

aime $\rightarrow$ VBP(like)

enfants $\rightarrow$ NNS(children)

J' $\rightarrow$ PRP(I)

lisent $\rightarrow$ VBP(read)

livres $\rightarrow$ NNS(books)

que $\rightarrow$ IN(that)

. $\rightarrow$.(.)

les $NNS_1 \rightarrow NP(NNS_1)$

$IN_1\ S_2 \rightarrow SBAR(IN_1\ S_2)$

$NP_1\ VP_2\ ._3 \rightarrow S(NP_1\ VP_2\ ._3)$

$PRP_1 \rightarrow NP(PRP_1)$

$VBP_1 \rightarrow VP(VBP_1)$

$VP_1\ NP_2 \rightarrow S(NP_2\ VP_1)$

$VBP_1\ NP_2\ SBAR_3 \rightarrow VP(VBP_1\ NP_2\ SBAR_3)$

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J' aime les livres que lisent les enfants .

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PRP

I aime les livres que lisent les enfants .

Translating with GHKM

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PRP VBP

I like les livres que lisent les enfants .

Translating with GHKM

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$\text{J'} \rightarrow \text{PRP(I)}$

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$\text{livres} \rightarrow \text{NNS(books)}$

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$. \rightarrow .(.)$

$\text{les NNS}_1 \rightarrow \text{NP(NNS}_1\text{)}$

$\text{IN}_1\ \text{S}_2 \rightarrow \text{SBAR(IN}_1\ \text{S}_2\text{)}$

$\text{NP}_1\ \text{VP}_2\ ._3 \rightarrow \text{S(NP}_1\ \text{VP}_2\ ._3\text{)}$

$\text{PRP}_1 \rightarrow \text{NP(PRP}_1\text{)}$

$\text{VBP}_1 \rightarrow \text{VP(VBP}_1\text{)}$

$\text{VP}_1\ \text{NP}_2 \rightarrow \text{S(NP}_2\ \text{VP}_1\text{)}$

$\text{VBP}_1\ \text{NP}_2\ \text{SBAR}_3 \rightarrow$
$\quad \text{VP(VBP}_1\ \text{NP}_2\ \text{SBAR}_3\text{)}$

PRP	VBP		NNS	IN	VBP		NNS	.
I	like	les	books	that	read	les	children	.

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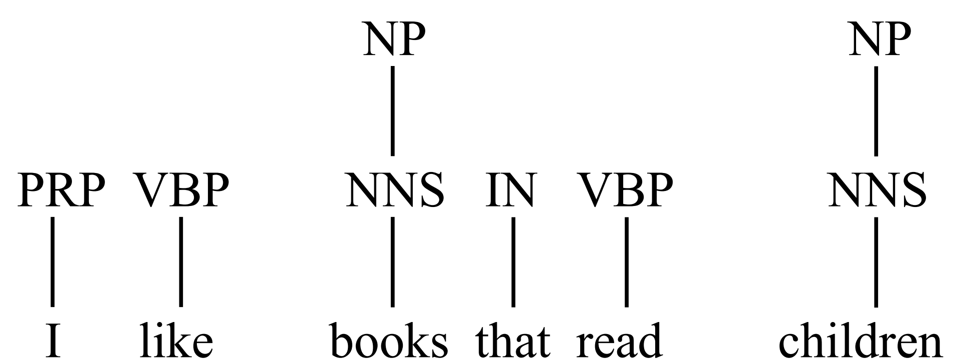

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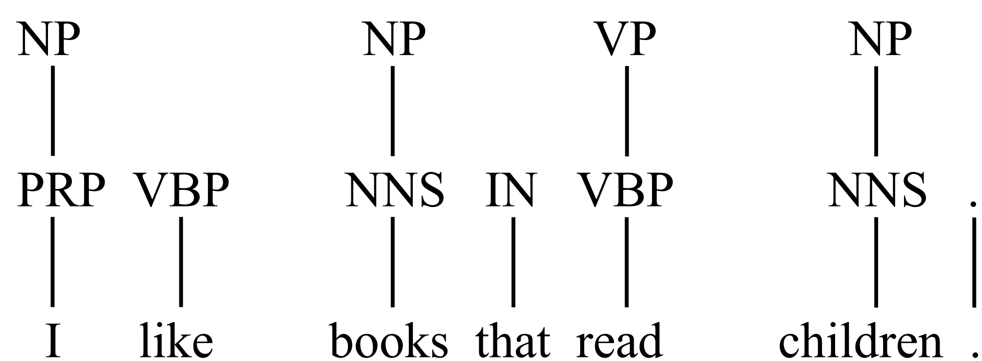

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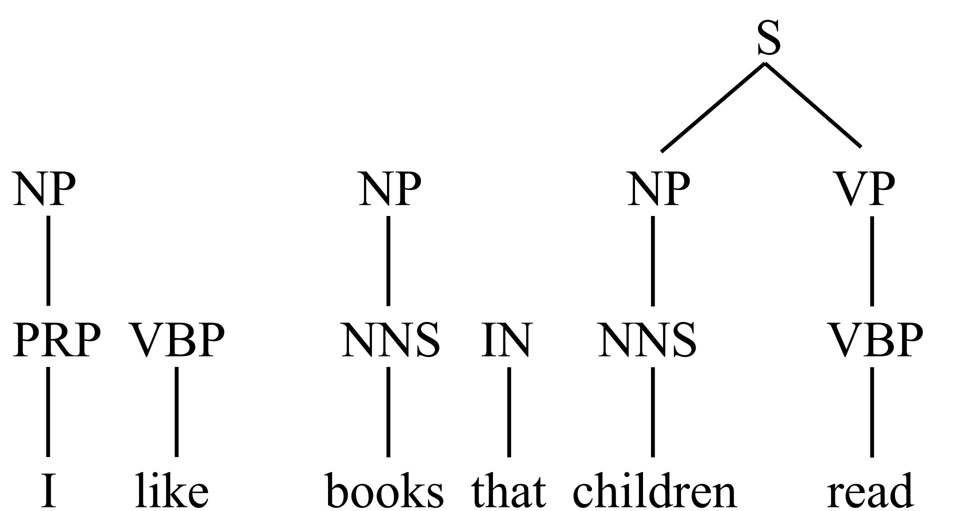

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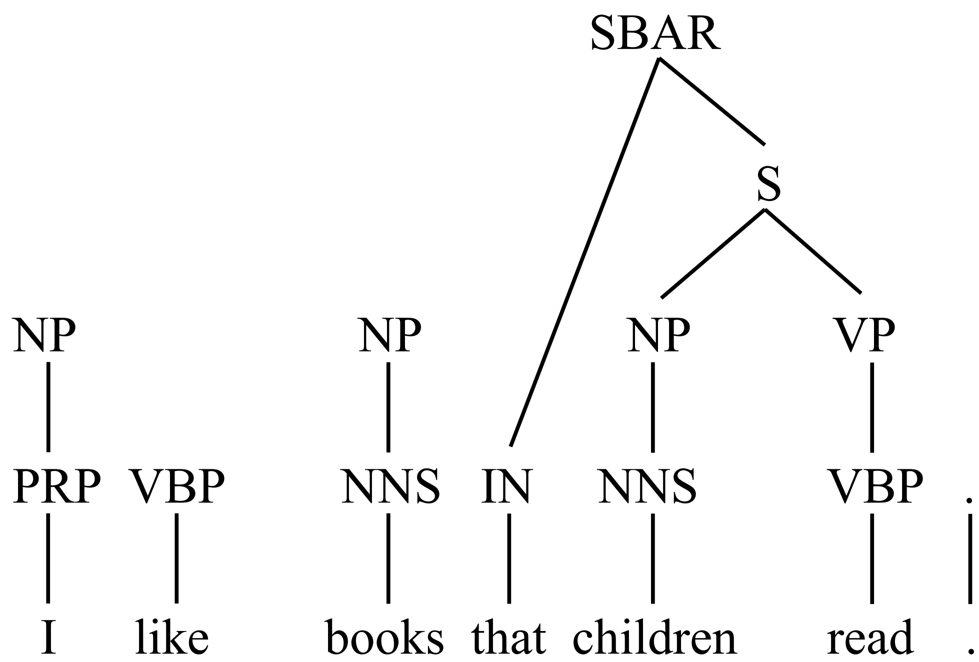

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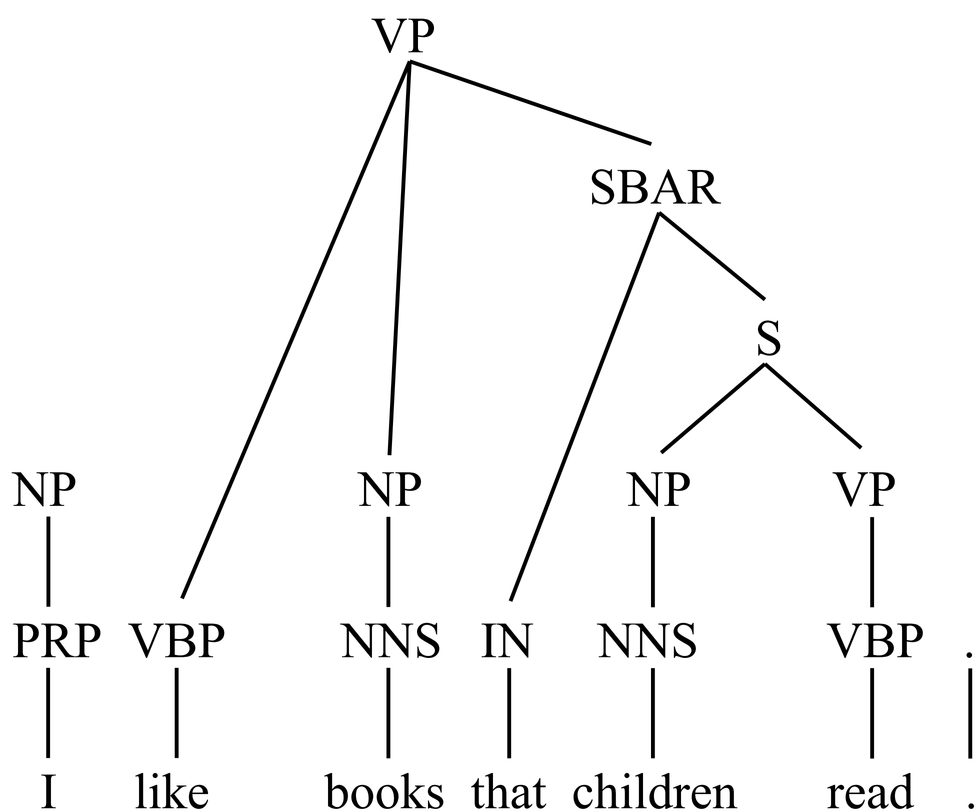

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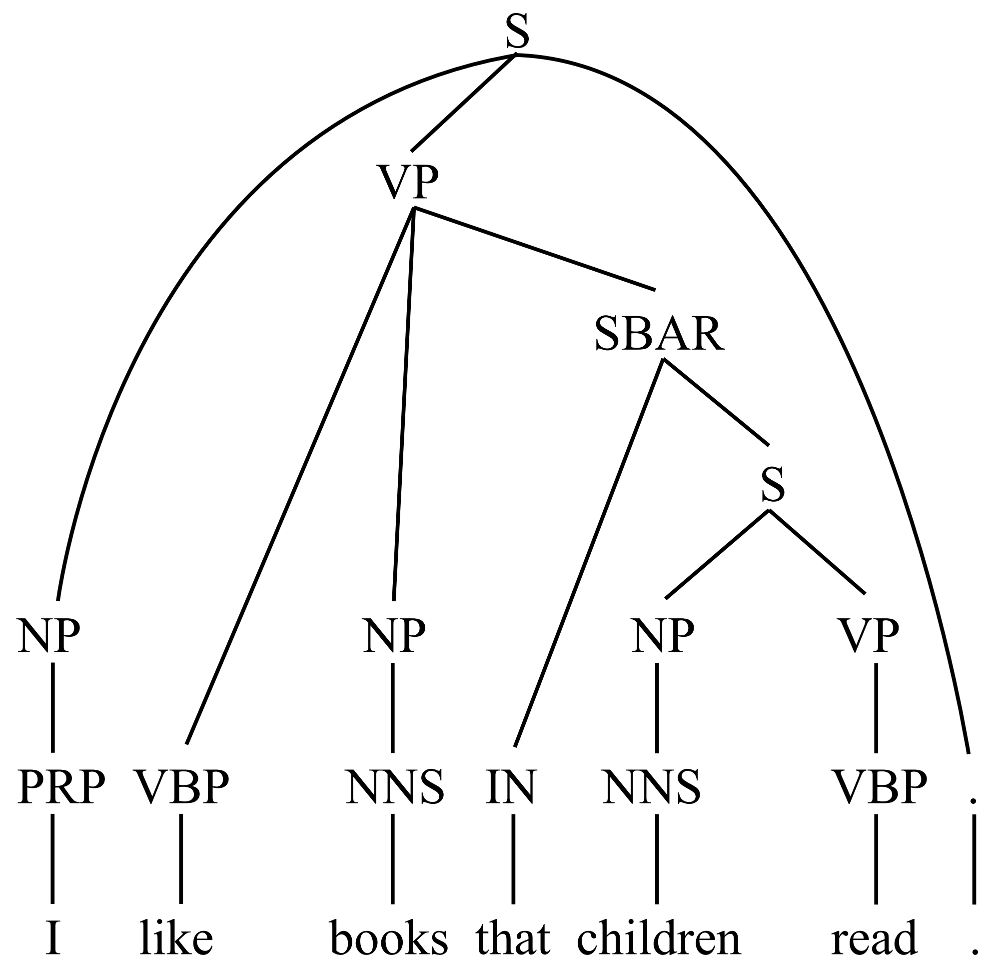


GHKM Summary

- Extract chunks of syntactic structure; recursively transform string into tree
- Decisions made:
  - Syntax on: Target side
  - Rule formalism: String-to-tree transducer
  - Input: String
  - Label space: Treebank
- Extensions and analysis: DeNeefe et al. [2007], Huck et al. [2014]

GHKM Pros and Cons

GHKM Pros and Cons

- More “native-looking” trees (LMs, etc.)
- No restrictions on rule shape or size

- Smaller label set than SAMT

- Can need big rules at top of tree
- No coverage for non-constituents
- Unary chains permit many label changes

Part 2

Tree-to-Tree Methods

Parse Trees on Both Sides

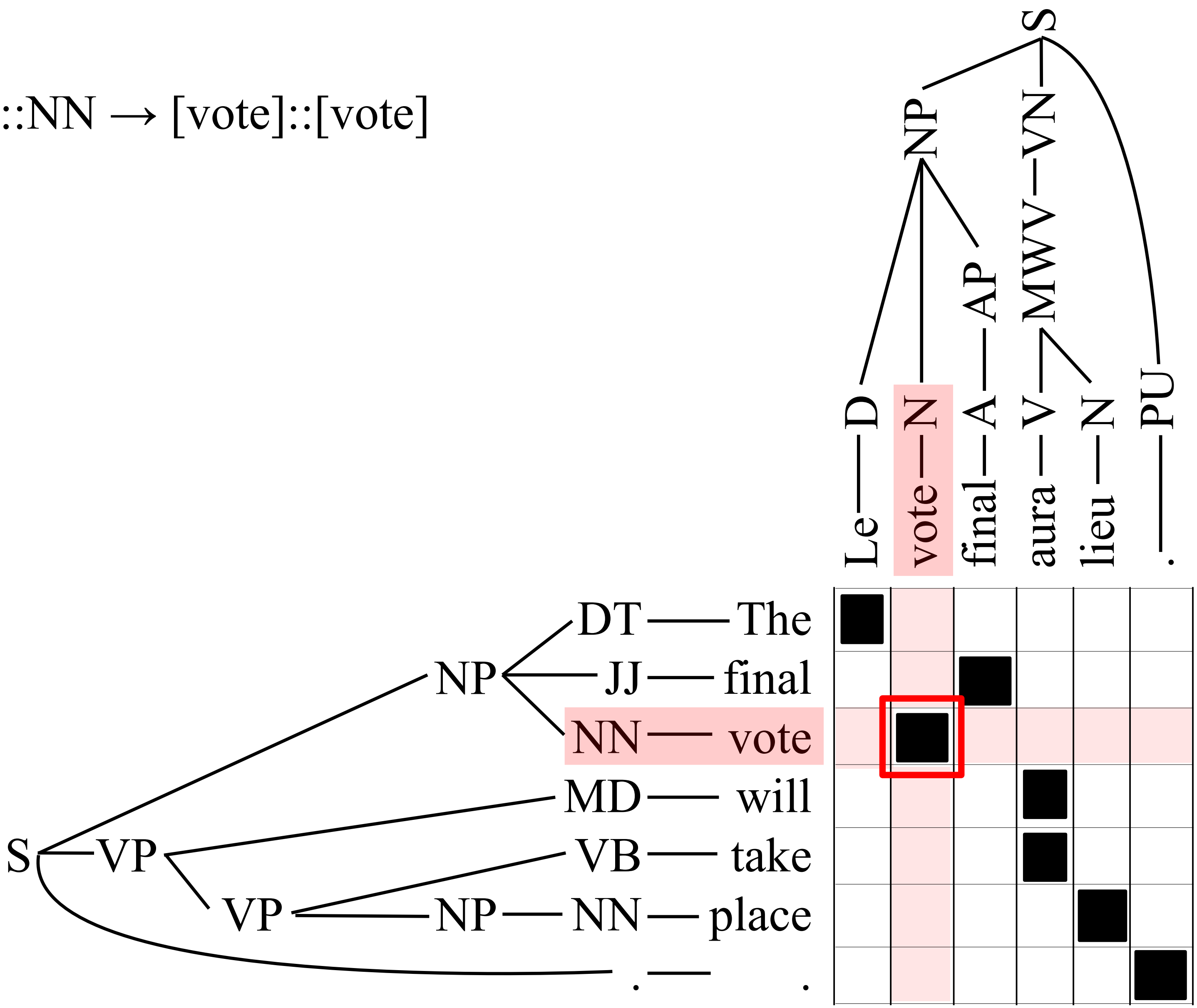
- Why add the source-side tree?
- Why could that also be a bad idea?

Parse Trees on Both Sides

- Why add the source-side tree?
  - Further disambiguate syntactic context
  - Could parse input and transform it: don't have to guess constituent boundaries
- Why could that also be a bad idea?
  - Could increase rule sparsity (e.g. labels)
  - Could hurt coverage if required to exactly match constituents on both sides
  - Only works for source and target languages that both have parsers

Tree-to-Tree Rule Extraction

N::NN → [vote]::[vote]



Tree-to-Tree Rule Extraction

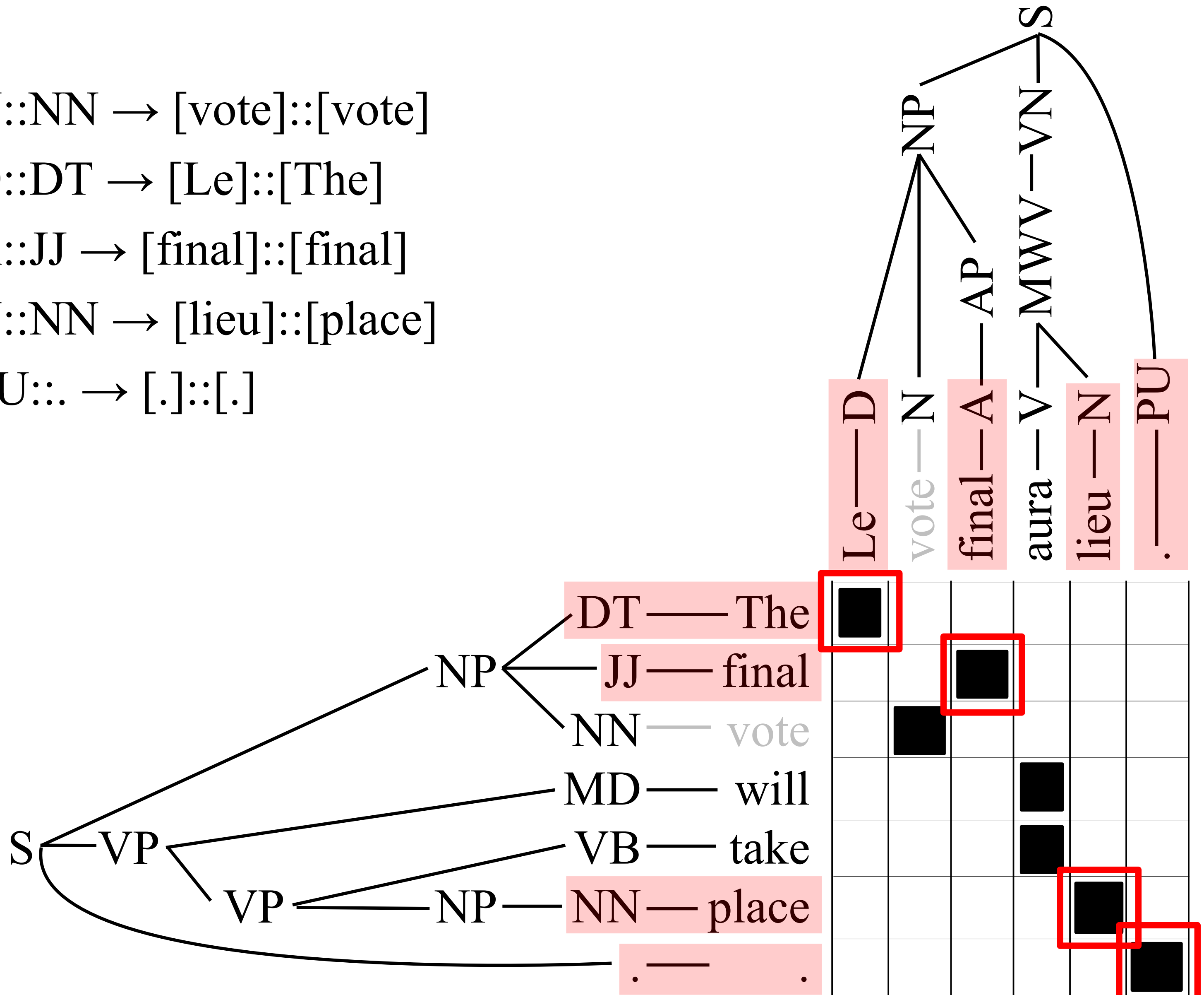
N::NN → [vote]::[vote]

D::DT → [Le]::[The]

A::JJ → [final]::[final]

N::NN → [lieu]::[place]

PU::. → [.]::[.]



Tree-to-Tree Rule Extraction

$\text{N::NN} \rightarrow \text{[vote]::[vote]}$

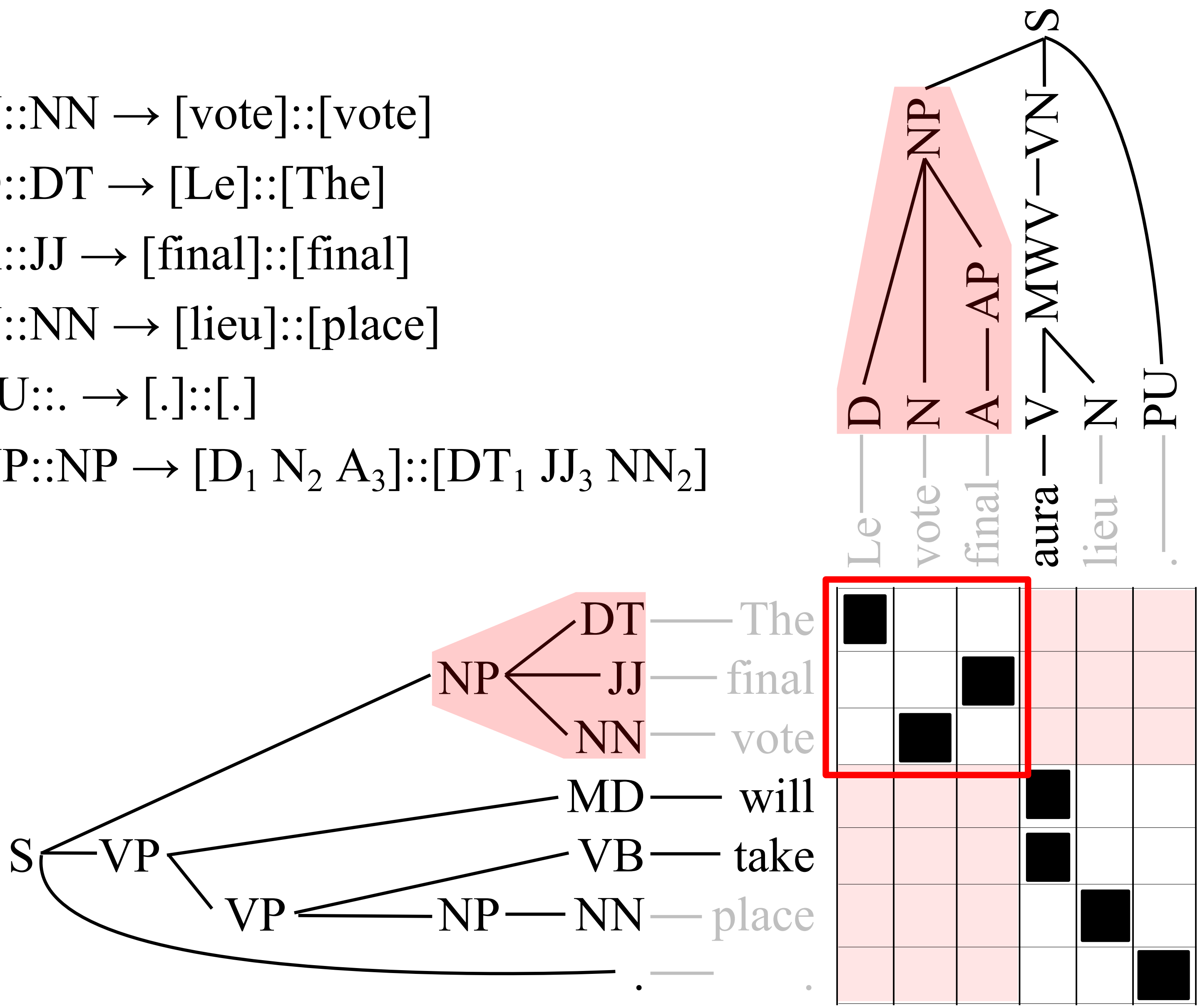
$\text{D::DT} \rightarrow \text{[Le]::[The]}$

$\text{A::JJ} \rightarrow \text{[final]::[final]}$

$\text{N::NN} \rightarrow \text{[lieu]::[place]}$

$\text{PU::.} \rightarrow \text{[.]::[.]}$

$\text{NP::NP} \rightarrow [\text{D}_1\ \text{N}_2\ \text{A}_3]\text{::}[\text{DT}_1\ \text{JJ}_3\ \text{NN}_2]$



Tree-to-Tree Methods

- Input is a string to jointly parse and translate (SCFG) [Lavie et al., 2008]
- Input is a tree to translate via tree transduction (STSG) [Xia and McCord, 2004]
- Input is a forest of packed variant trees to translate via transduction [Liu et al., 2009]

Tree-to-Tree Relaxations

- Use SAMT labeling instead [Chiang, 2010]
- Insert "virtual" nodes into the tree to cover partial constituents [Ambati and Lavie, 2008; Hanneman et al., 2011]
- Allow rules to replace one subtree with multiple (STSSG) [Zheng et al., 2008]
- Or ignore the target-side tree entirely…

Part 3

Tree-to-String Methods

Tree-to-String Translation

- Extract chunks of syntactic structure; recursively transform tree into string
- Why model only the source tree?
- Do we need a new rule formalism?

Tree-to-String Translation

- Extract chunks of syntactic structure; recursively transform tree into string
- Why model only the source tree?
  - Take tree input at run time: don’t have to guess constituent bounds
  - Therefore very fast and no pruning!
- Do we need a new rule formalism?
  - Still STSG: just flip direction of GHKM-like rules
  - Could also use SCFG

Tree-to-String Methods

- Input is a tree to translate via transduction [Huang et al., 2006; Liu et al., 2006]
- Input is a tree where nodes can be inserted, permuted, or translated [Yamada and Knight, 2001]
- Input is a forest of packed variant trees to translate via transduction [Mi et al., 2008]
- Analysis: Neubig and Duh [2014]

Part 4

Grand Summary

You Should Now Know…

- Why (linguistic) syntax in MT is desirable
- Some of the decision points involved
- Two ways of deciding: SAMT and GHKM
- How to extract/apply SCFG and STSG rules
- About trade-offs involving labels and tree constraints
- That if you want to know more…

There are Lots of Good Papers

- Ambati and Lavie (2008), "Improving Syntax Driven Translation Models by Re-Structuring Divergent and Non-Isomorphic Parse Tree Structures." Proceedings of AMTA.
- Chiang (2010), "Learning to Translate with Source and Target Syntax." Proceedings of ACL.
- DeNeefe et al. (2007), "What Can Syntax-Based MT Learn from Phrase-Based MT?" Proceedings of EMNLP.
- Galley et al. (2004), "What's in a Translation Rule?" Proceedings of NAACL.
- Galley et al. (2006), "Scalable Inference and Training of Context-Rich Syntactic Translation Models." Proceedings of ACL.
- Hanneman et al. (2011), "A General-Purpose Rule Extractor for SCFG-Based Machine Translation." Proceedings of SSST-5.
- Huang et al. (2006), "Statistical Syntax-Directed Translation with Extended Domain of Locality." Proceedings of AMTA.
- Huck et al. (2014), "Preference Grammars and Soft Syntax Constraints for GHKM Syntax-Based Statistical Machine Translation." Proceedings of SSST-8.
- Lavie et al. (2008), "Syntax-Driven Learning of Sub-Sentential Translation Equivalents and Translation Rules from Parsed Parallel Corpora." Proceedings of SSST-2.
- Liu et al. (2006), "Tree-to-String Alignment Template for Statistical Machine Translation." Proceedings of ACL.

There are Lots of Good Papers

- Liu et al. (2009), "Improving Tree-to-Tree Translation with Packed Forests." Proceedings of ACL.
- Mi et al. (2008), "Forest-Based Translation." Proceedings of ACL.
- Neubig and Duh (2014), "On the Elements of an Accurate Tree-to-String Machine Translation System." Proceedings of ACL.
- Venugopal et al. (2009), "Preference Grammars: Softening Syntactic Constraints to Improve Statistical Machine Translation." Proceedings of NAACL.
- Xia and McCord (2004), "Improving a Statistical MT System with Automatically Learned Rewrite Patterns." Proceedings of COLING.
- Zhang et al. (2008), "A Tree Sequence Alignment-Based Tree-to-Tree Translation Model." Proceedings of ACL.
- Zollmann and Venugopal (2006), "Syntax Augmented Machine Translation via Chart Parsing." Proceedings of WMT.
- Zollmann (2011), "Learning Multiple-Nonterminal Synchronous Grammars for Statistical Machine Translation." Ph.D. thesis, Carnegie Mellon University.

Any questions?