Memory Usage as a Measure of Structural Complexity in Minimalist Parsing

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Oct 30, 2019

One Big Question

(How much) does grammatical structure matter in sentence processing?

The MG Parsing Project

Syntactic complexity $\Leftrightarrow$ *Parser behavior* $\Leftrightarrow$ *Processing difficulty*

The Goal

- Can we give a *maximally simple* parsing model that derives off-line processing effects purely from memory usage?

Outline

1 Formal Models of Sentence Processing

2 Parsing Minimalist Grammars

3 Case Study: Italian Postverbal Subjects

4 Case Study: Gradience in Island Effects (in English)

5 Conclusion

A Trivial (?) Observation

Not All Sentences Are Processed Equally

- Center embedding VS Right embedding
  - RE The woman saw the boy that heard the man that left.
  - CE The woman the boy (that) the man that left heard saw.
- Subject VS object relative clauses
  - SRC I saw the horse that kicked the wolf
  - ORC I saw the horse that the wolf kicked
- Attachment preferences
  - 1a. I saw [a girl with the telescope]
  - 1b. I [saw a girl] [with the telescope]

Which aspects of grammar influence sentence processing?

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Which aspects of grammar influence sentence processing?

Sounds familiar?

Which aspects of grammar influence sentence processing?

- What is the relation between grammatical operations and cognitive processes?

Derivational Theory of Complexity (Miller and Chomsky, 1963)

- **One-to-one mapping** between processing complexity and length of a derivation
  (Fodor & Garrett 1967; Berwick & Weinberg 1983)
- Essentially: there is a **cost** to mental computations.

- What is the right notion of syntactic derivation?
- What is costly? And why?

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A Formal Model of Sentence Processing

The Power of Explicit Grammar Formalisms

We can relate formal models of competence to formal models of performance in transparent, quantifiable ways.

The Model

1. a formalization of syntax → Minimalist grammars
2. a theory of how structures are built → top-down parser
3. a linking theory → complexity metrics for memory usage

Perks

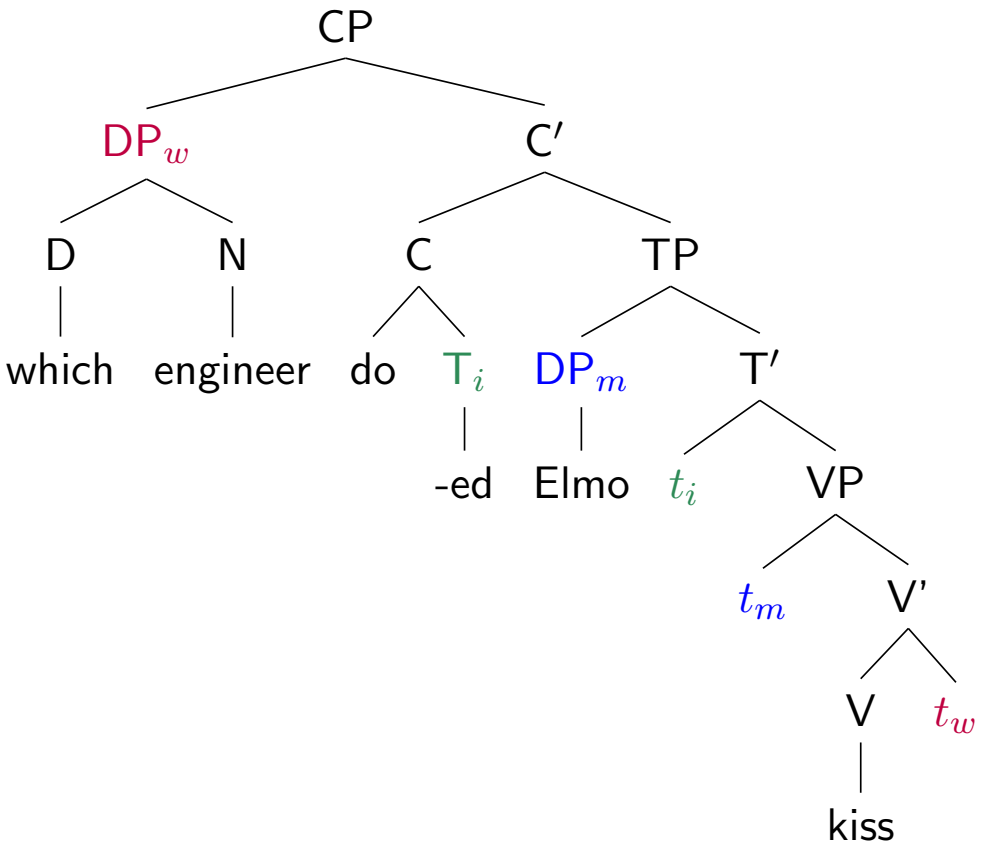
- sensitive to fine-grained structural differences
- bridge between theoretical syntax and processing data

Minimalist Grammars (MGs)

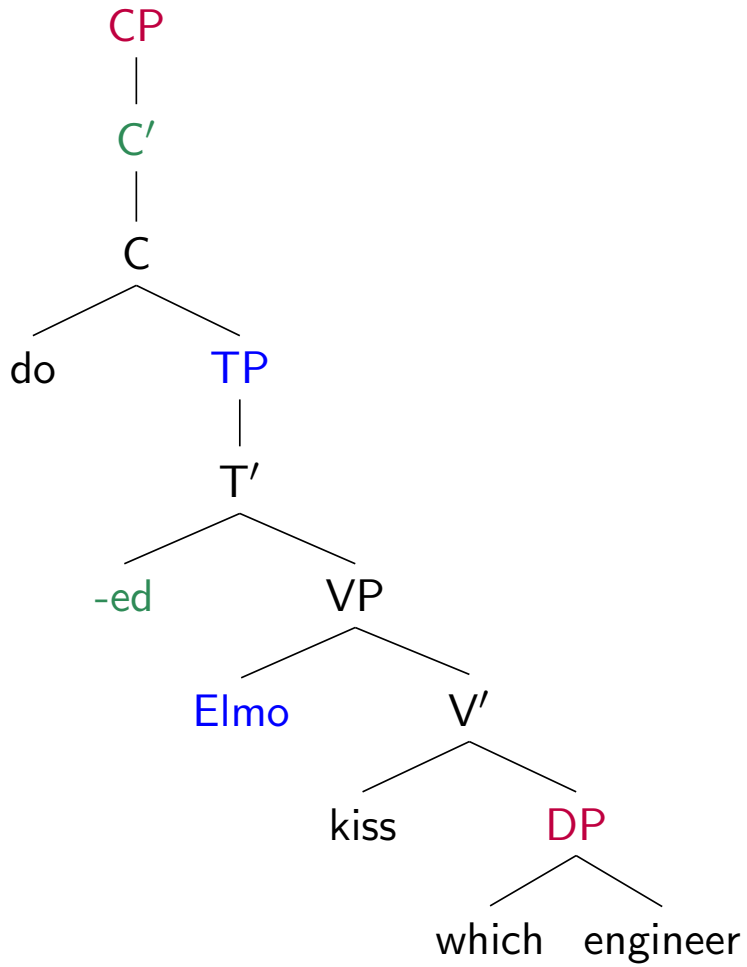
We need a formal model of syntactic structures...

- Minimalist grammars (**MGs**) are a formalization of Chomskyan syntax (Chomsky 1995; Stabler 1997)
- Grammar is just a finite list of feature-annotated lexical items (LIs)
- Operations: **Merge** and **Move**
- Essentially: CFGs with a more complicated mapping from trees to strings

MG Syntax: Derivation Trees



Phrase Structure Tree



Derivation Tree

Incremental Top-Down Parsing

How (Modified) recursive descent parser (Stabler 2013)

Strategy Hypothesize structure top-down and verify that words in structure match input string (*string-driven recursive descent*).

▶ • Who • does • Salem • T • mock

step 1 CP is conjectured
step 2 CP expands to C′
step 3 C′ expands to does and TP
step 4 TP expands to Salem and T′
step 5 T′ expands to T and VP
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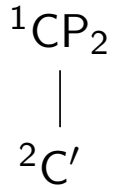

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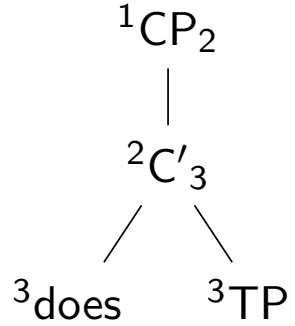

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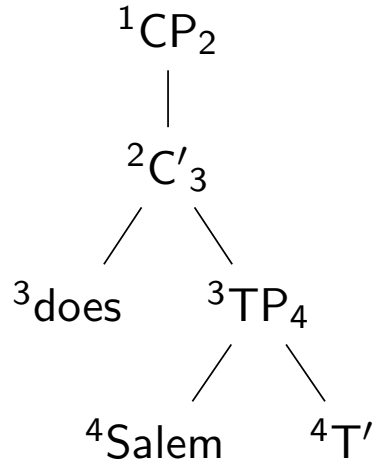

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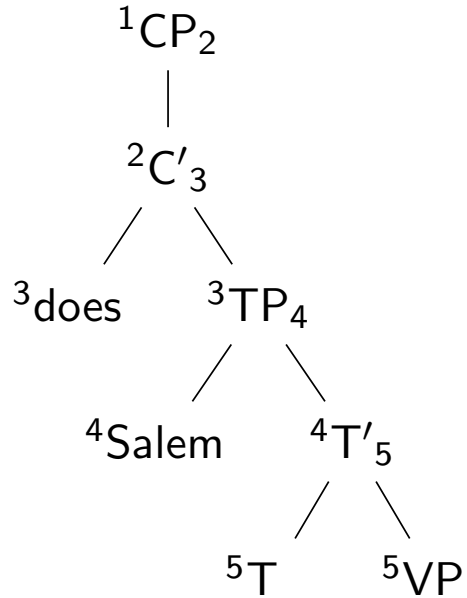

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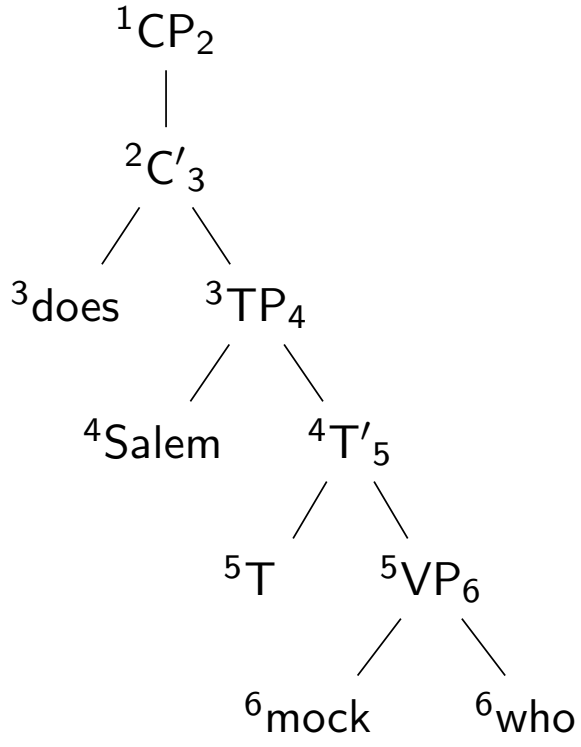

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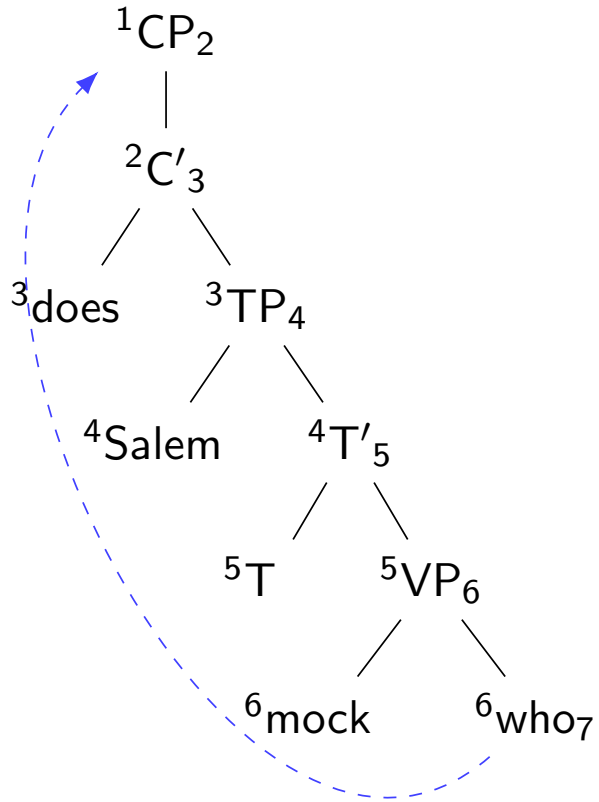

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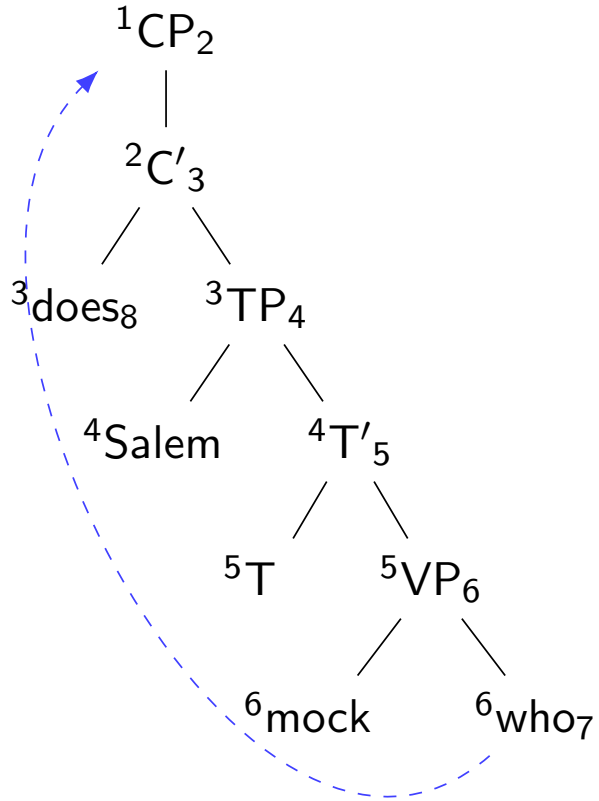

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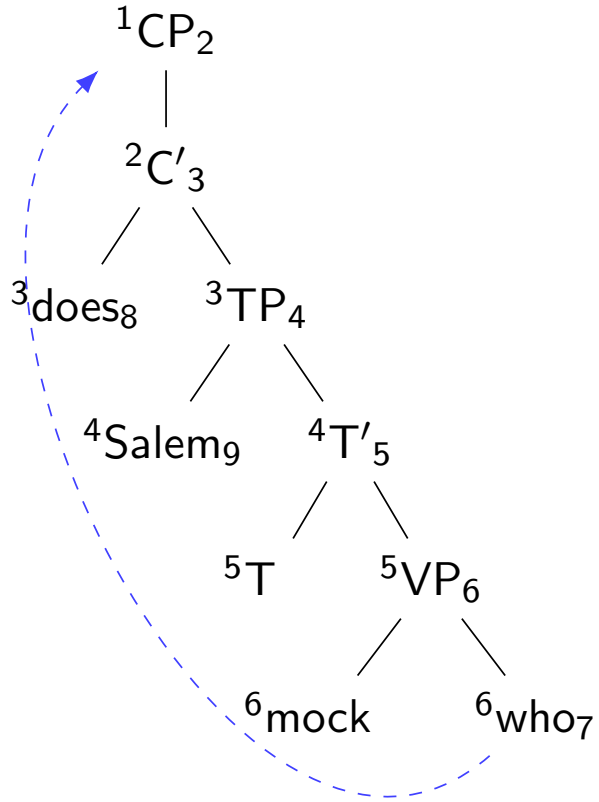

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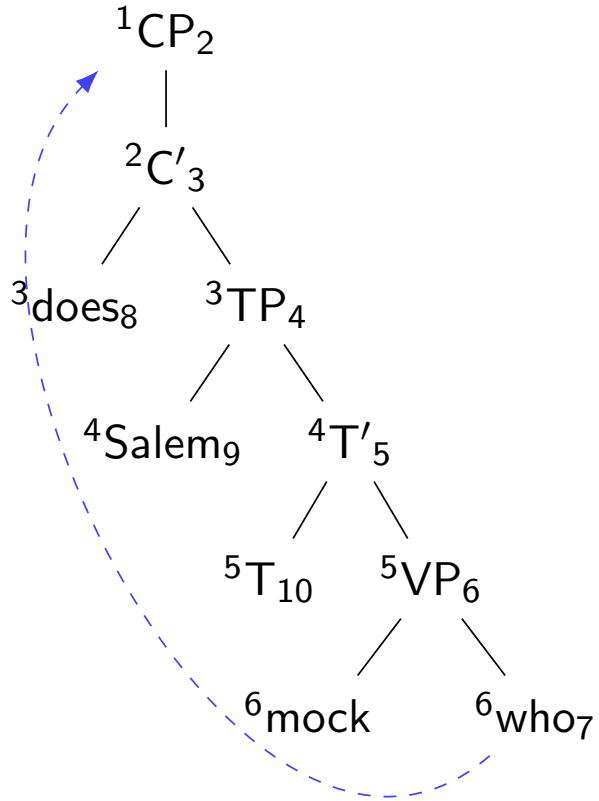

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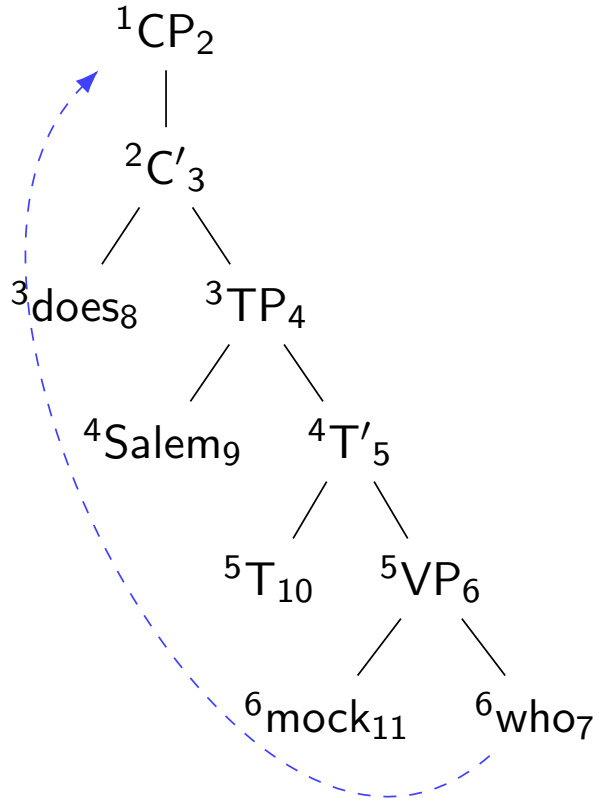

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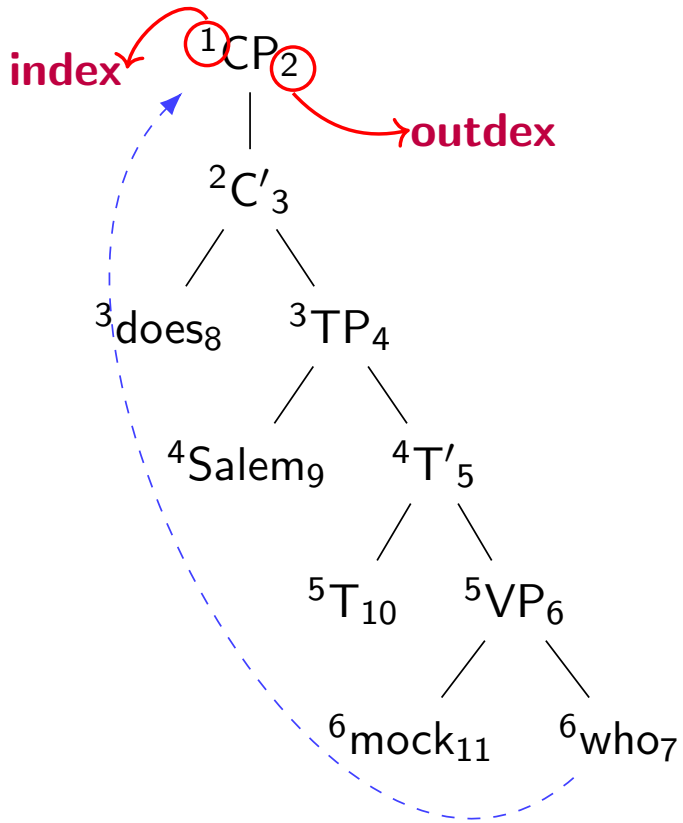

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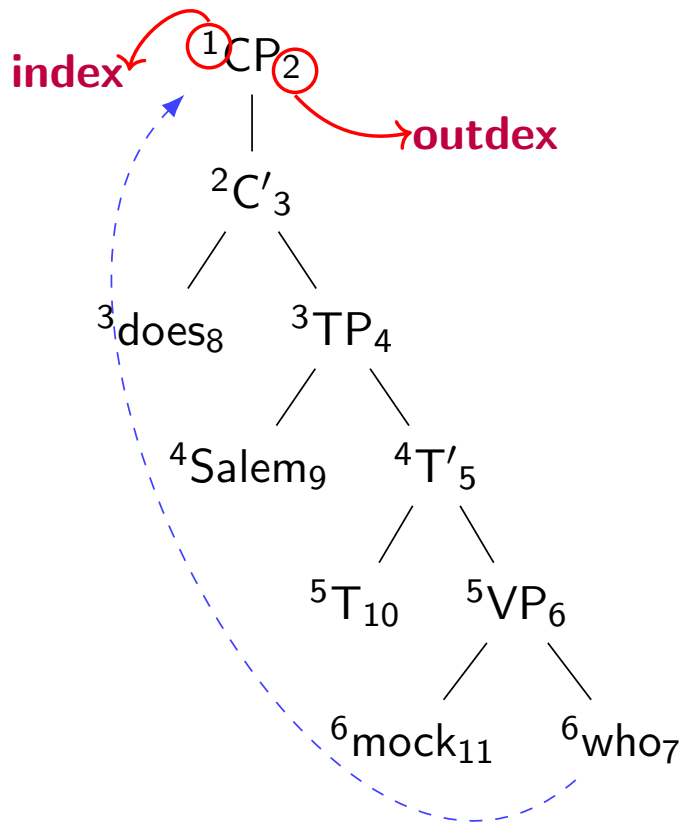

Index and Outdex are our connection to memory!

Memory-Based Complexity Metrics

- **Memory usage**:

Tenure how long a node is kept in memory
Size how much information is stored in a node
⇒ Intuitively, the length of its movement dependency!

- These can be formalized into **complexity metrics** (Kobele et al. 2012)

MaxTenure $max(\{\text{tenure-of}(n) | n \text{ a node of the tree}\})$
SumSize $\sum_{m \in M} size(m)$
Ranked $\langle MaxTenure, SumSize \rangle$

- Currently: **40 base metrics!**

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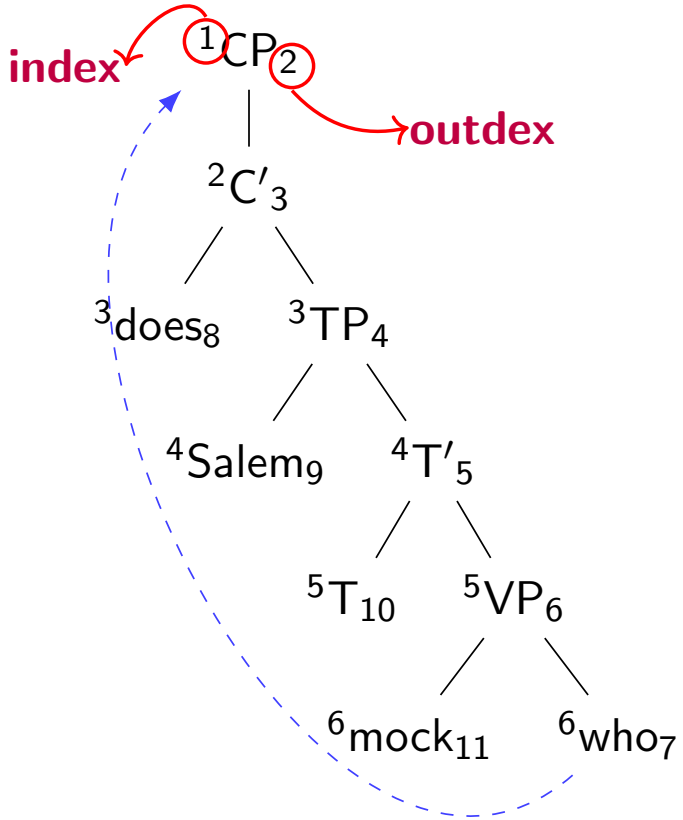
Space of Possible Metrics?

<MaxT,SumS> makes correct predictions cross-linguistically!

- Right < center embedding (Kobele et al. 2012)
- Crossing < nested dependencies (Kobele et al. 2012)
- SC-RC < RC-SC (Graf & Marcinek 2014)
- SRC < ORC (Graf et al. 2017)
  - English
  - Korean
  - Japanese
- Postverbal subjects in Italian (De Santo 2019)
- ...

Computing Metrics: An Example

1. **Tenure** how long a node is kept in memory
2. **Size** (Intuitively) the length of movement dependencies!



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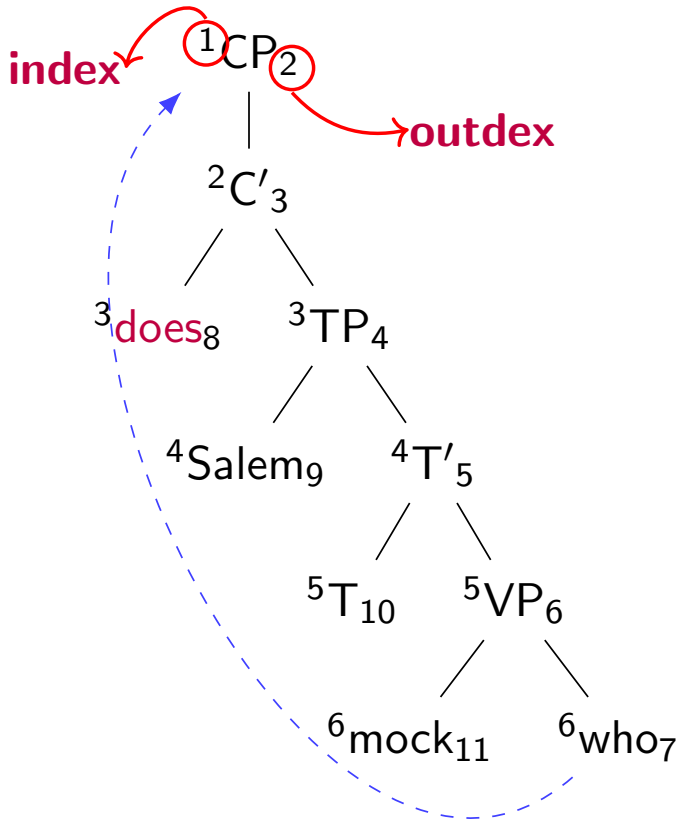

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Tenure($does$**)** $= 8 - 3 = 5$

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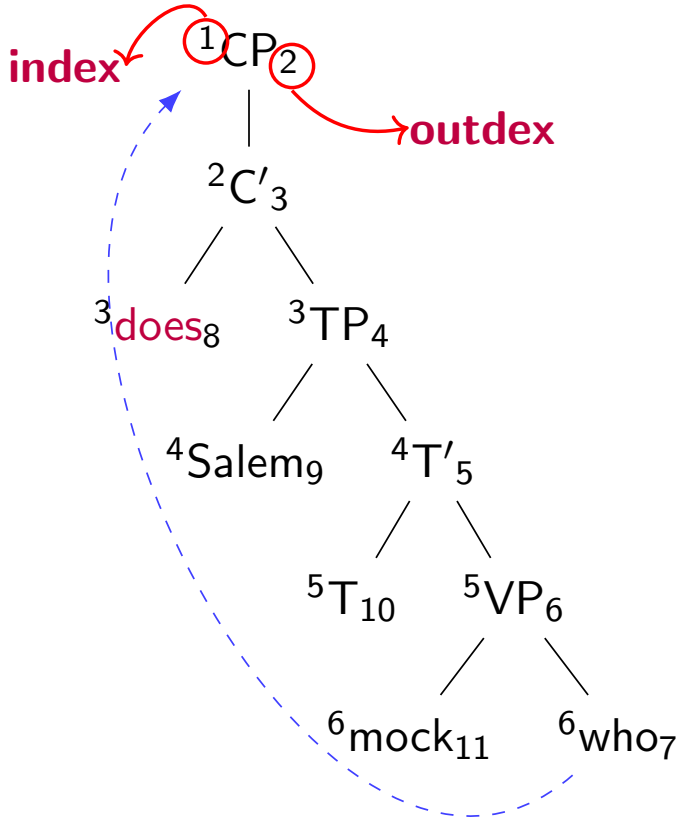

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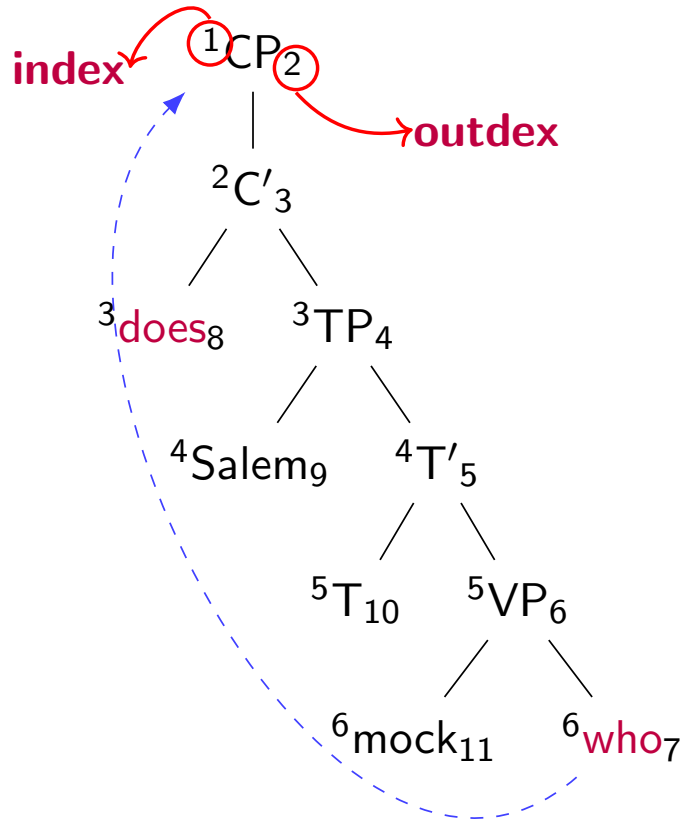

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   index(origin(m)) − index(landing(m))

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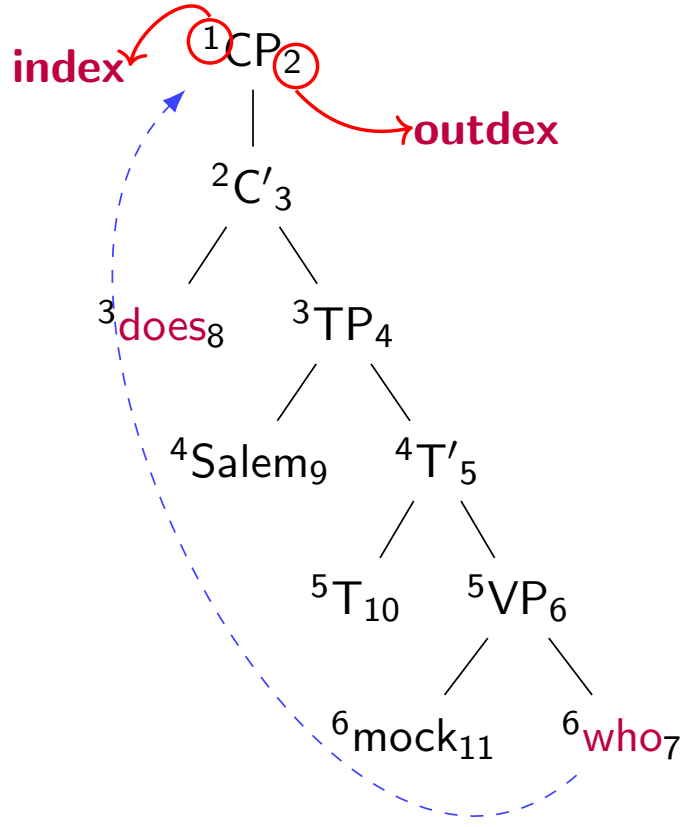

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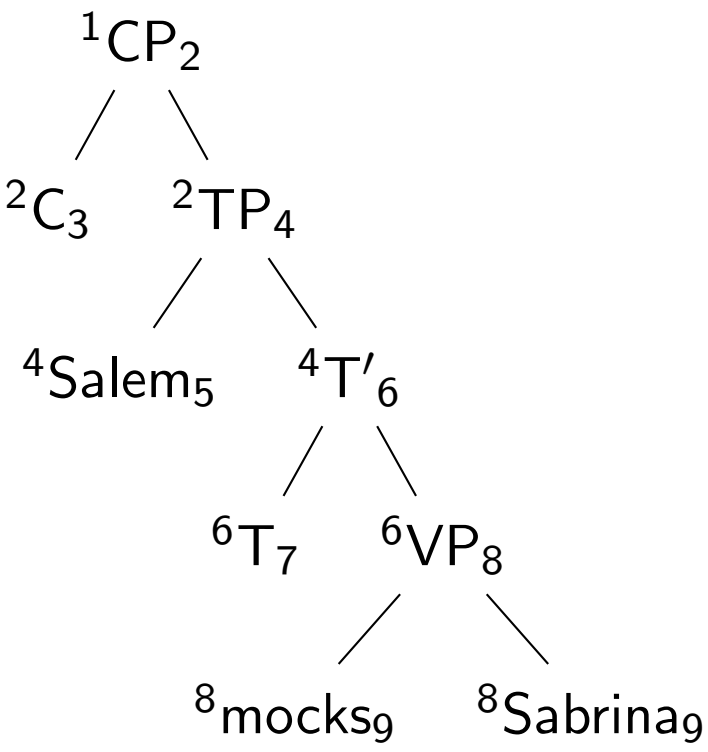
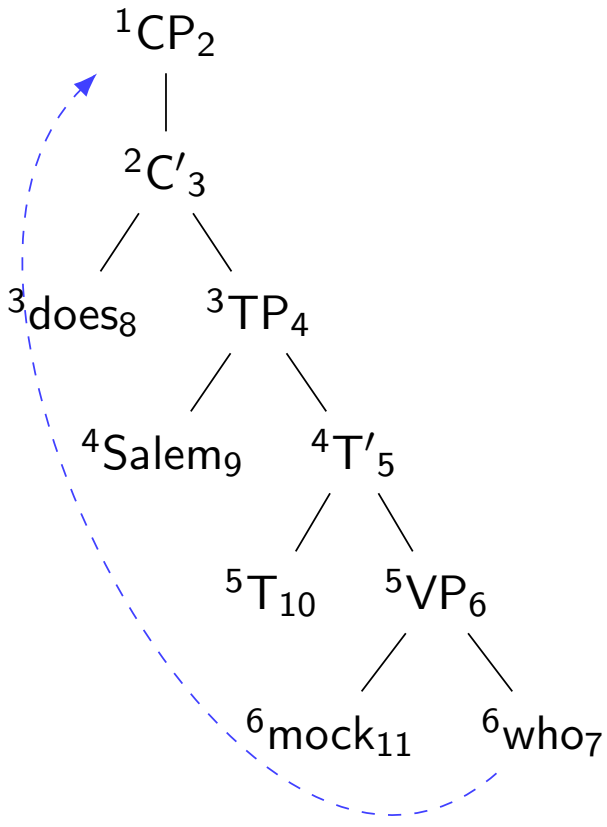
Size$(who) = 6 - 1 = 5$
SumSize $= \sum$**Size**$(who) = 5$

Contrasting Derivations

MaxTenure $= 2$

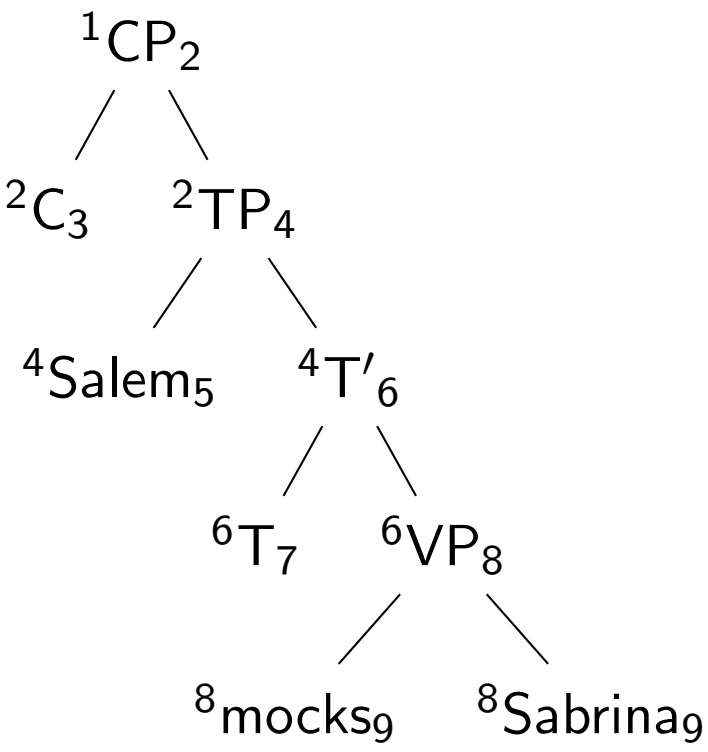


MaxTenure $= 5$

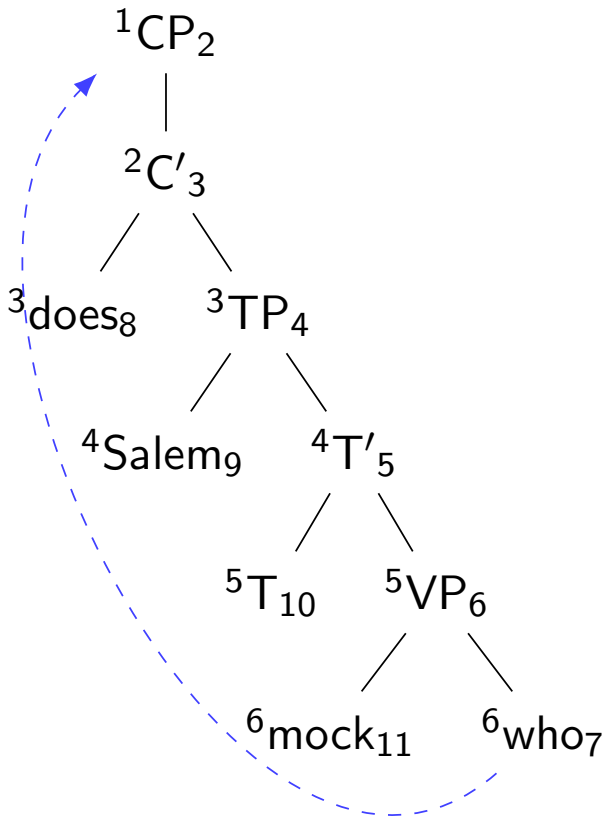


Contrasting Derivations

MaxTenure $= 2$
SumSize $= 0$



MaxTenure $= 5$
SumSize $= 5$



Summary of the Approach

General Idea

(Kobele et al. 2012; Gerth 2015; Graf et al. 2017)

- pick competing derivations
- evaluate metrics over each
- compare parser's prediction to off-line processing data

Simplifying Assumptions

- Parser as an Oracle $\Rightarrow$ Discard beam search
- factor out cost of finding correct parse

A Case Study: Italian Postverbal Subjects

Asymmetries in Italian Relative Clauses

Italian speakers conform to the general cross-linguistic preference for SRC over ORC (Adani et al. 2010; Arosio et al. 2008)

(1) Il cavallo che ha inseguito i leoni
The horse that has chased the lions
"The horse that chased the lions" **SRC**

(2) Il cavallo che i leoni hanno inseguito
The horse that the lions have chased
"The horse that the lions chased" **ORC**

Postverbal Subjects and Ambiguity

Italian allows for postverbal subjects, making some sentences ambiguous (De Vincenzi 1991):

(3) Il cavallo che ha inseguito il leone
The horse that has chased the lion

a. "The horse that chased the lion" **SRC**

b. "The horse that the lion chased" **ORCp**

SRC > ORCp

Agreement can disambiguate:

(4) Il cavallo che hanno inseguito i leoni
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(4) Il cavallo che hanno inseguito i leoni
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Asymmetries in Italian Relative Clauses [cont.]

(1) Il cavallo che ha inseguito i leoni
The horse that has chased the lions
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The horse that the lions have chased
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The horse that have chased the lions
"The horse that the lions chased" **ORCp**

SRC > ORC > ORCp

Modeling Assumptions

Reminder:

- Parsing strategy
  ⇒ Top-down parser
- Complexity Metrics
  ⇒ MaxTenure and SumSize

Degrees of freedom: Syntactic analyses

1. RC constructions → (Kayne 1994)
2. Postverbal subjects → (Belletti & Leonini 2004)

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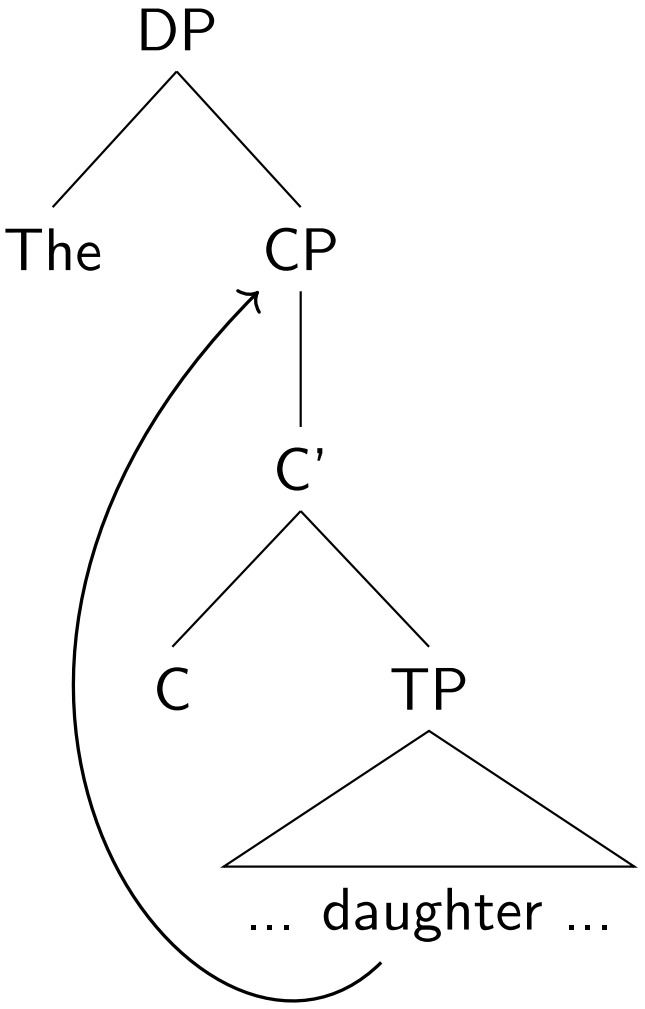
- RC is selected by an external D^0
- the RC head is a nominal constituent
- the RC head raises from its base position to [Spec, CP]



$[_{DP}$ The $[_{CP}$ daughter$_i$ [that t_i was on the balcony]]]

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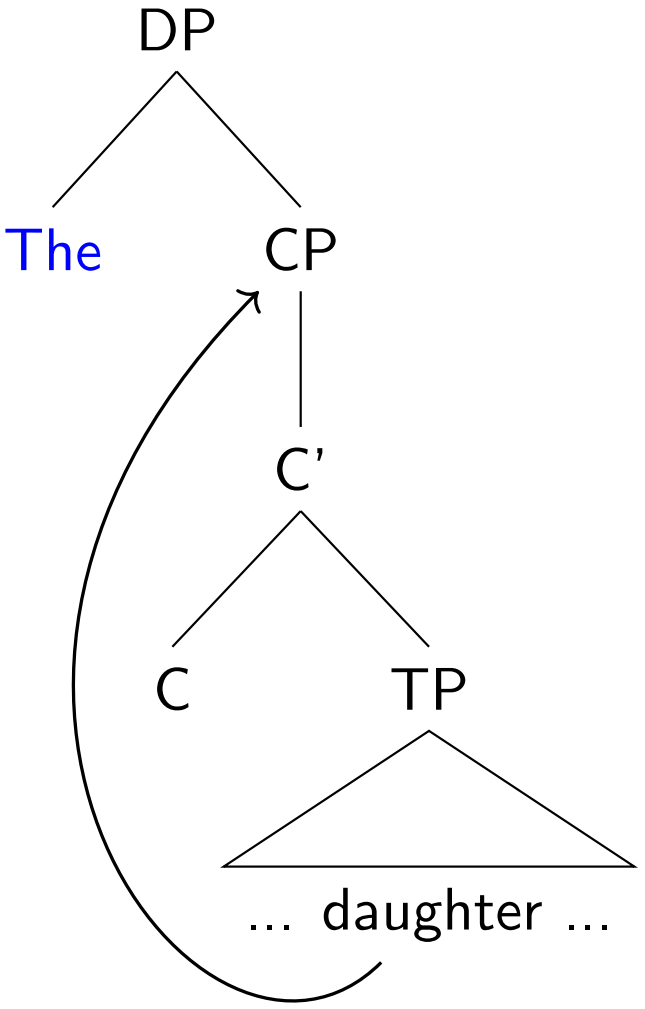

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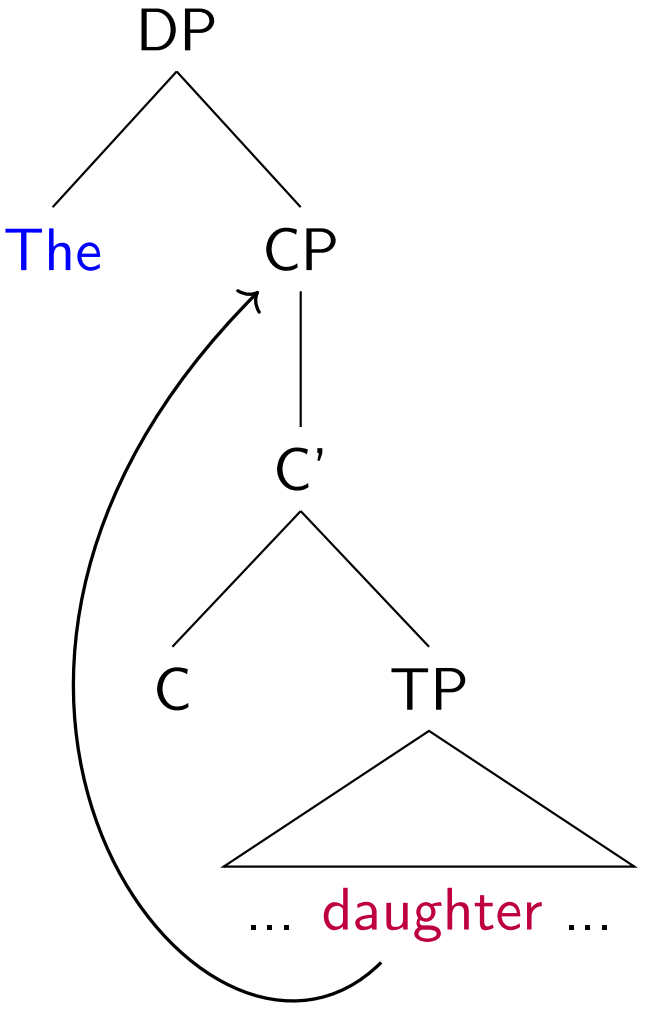

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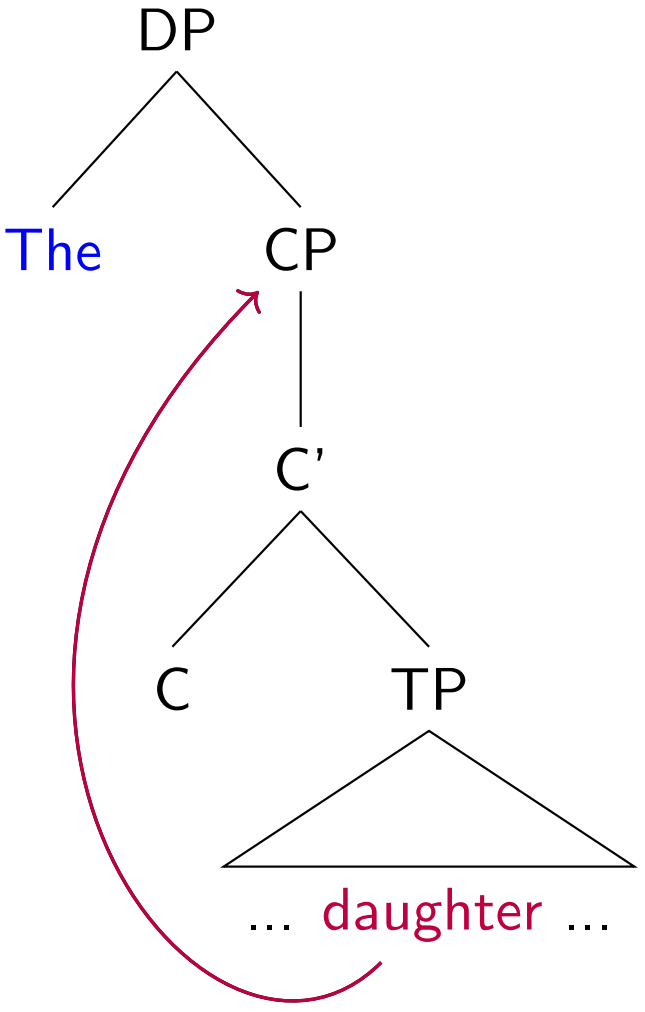

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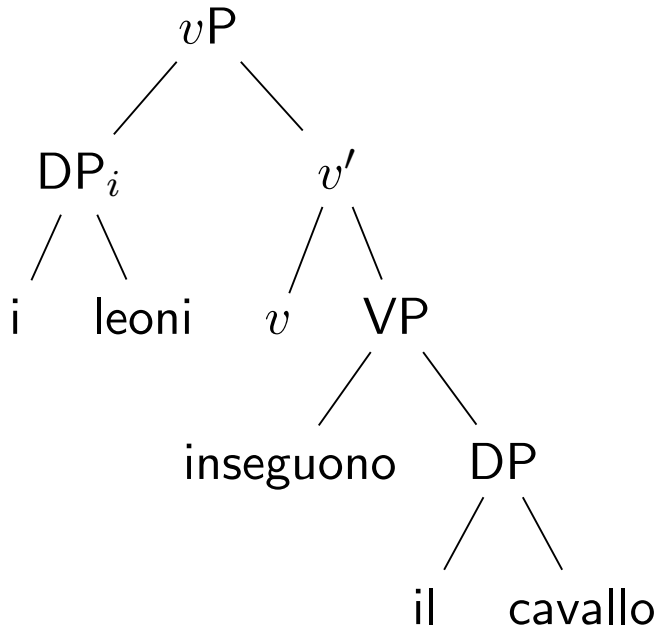
Postverbal Subjects (Belletti & Leonini 2004)

(5) Inseguono il cavallo i leoni
Chase the horse the lions
"The lions chase the horse"

- the subject DP raises to Spec, FocP
- The whole vP raises to Spec,TopP
- an expletive *pro* is base generated in Spec,TP



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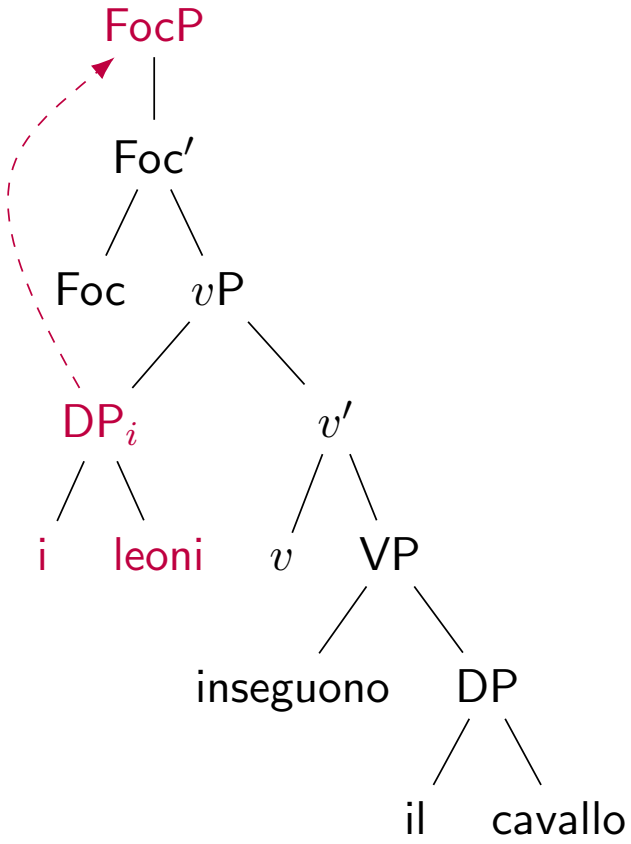

Postverbal Subjects (Belletti & Leonini 2004)

(7) Inseguono il cavallo i leoni
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- the subject DP raises to Spec, FocP
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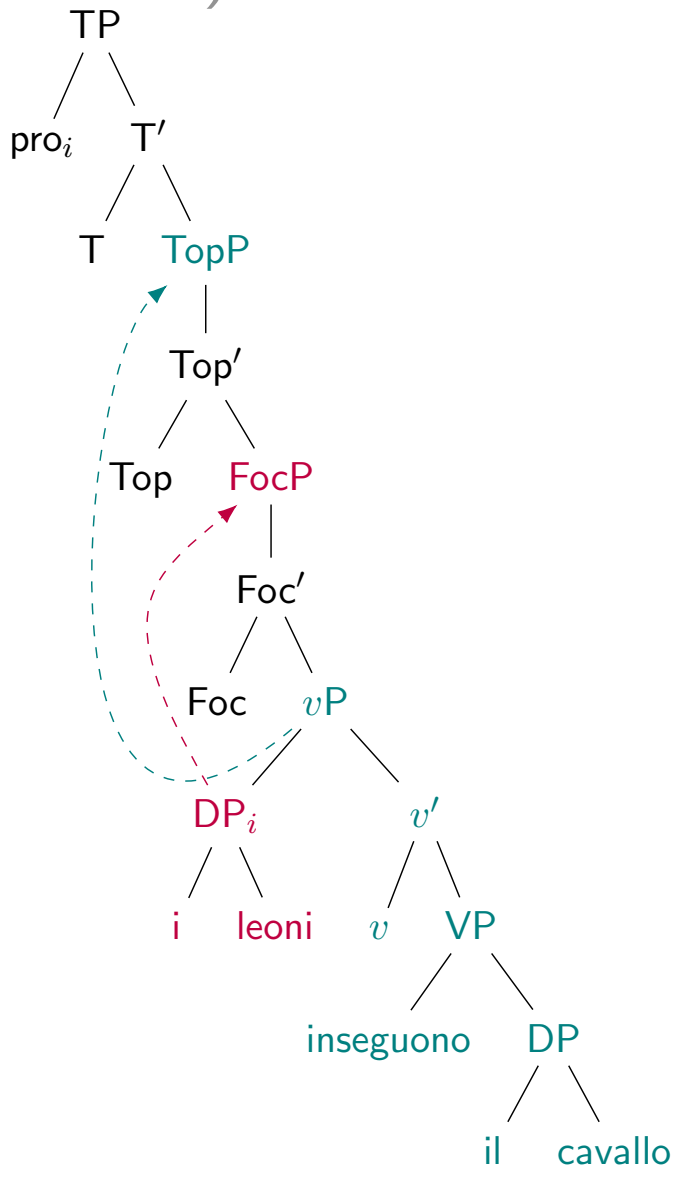

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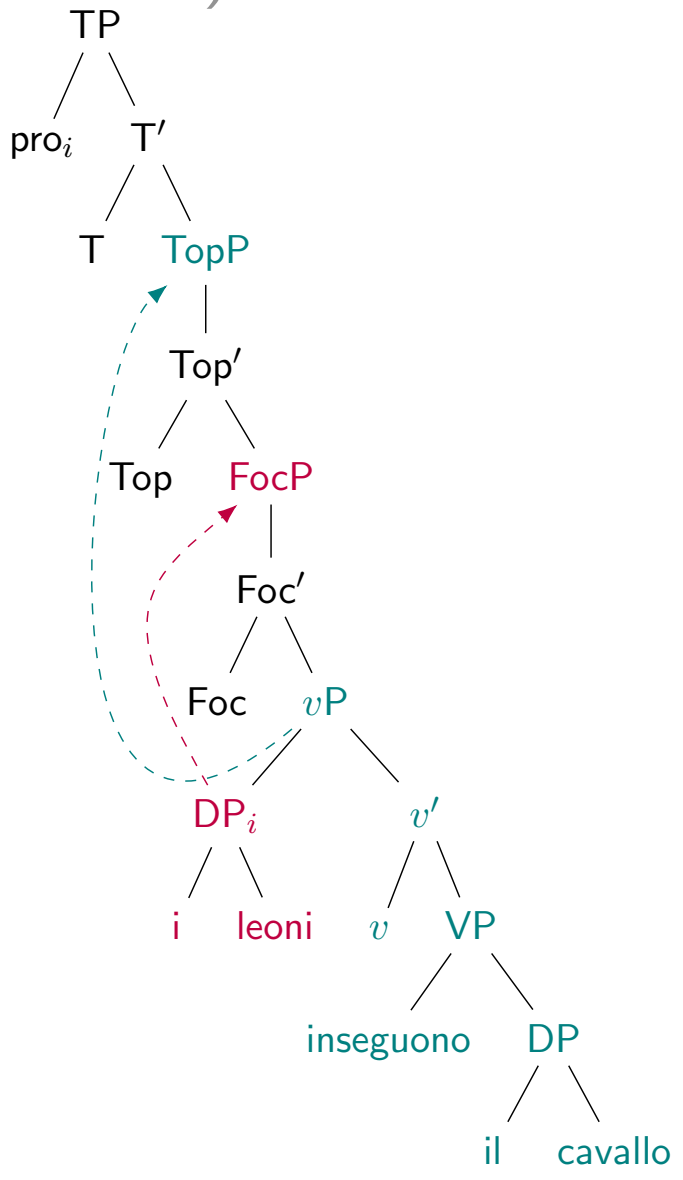

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	SRC	>	ORC	>	ORCp
MaxTenure	8/che		11/ha		16/Foc
SumSize	18		24		31

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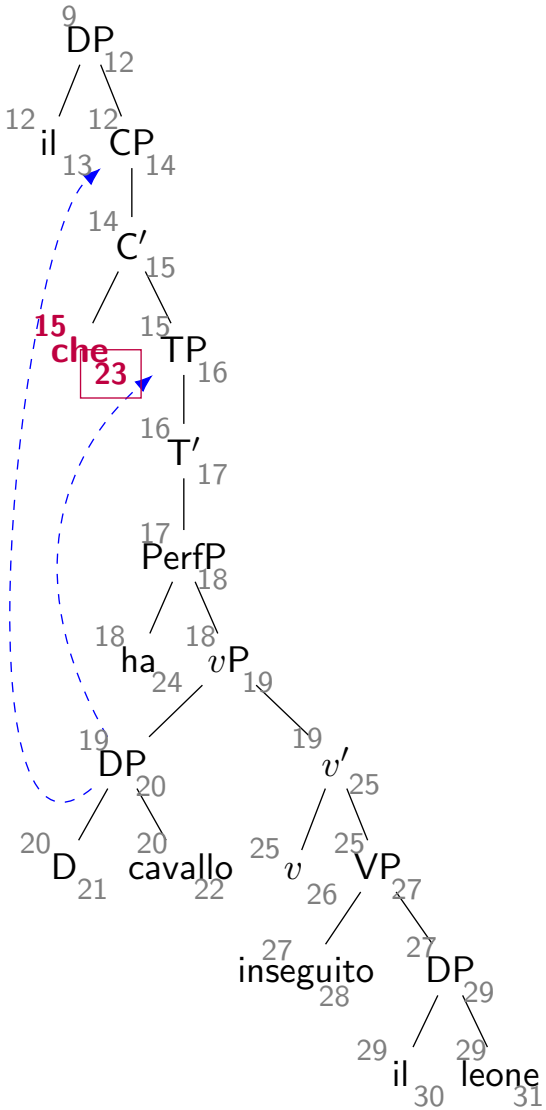

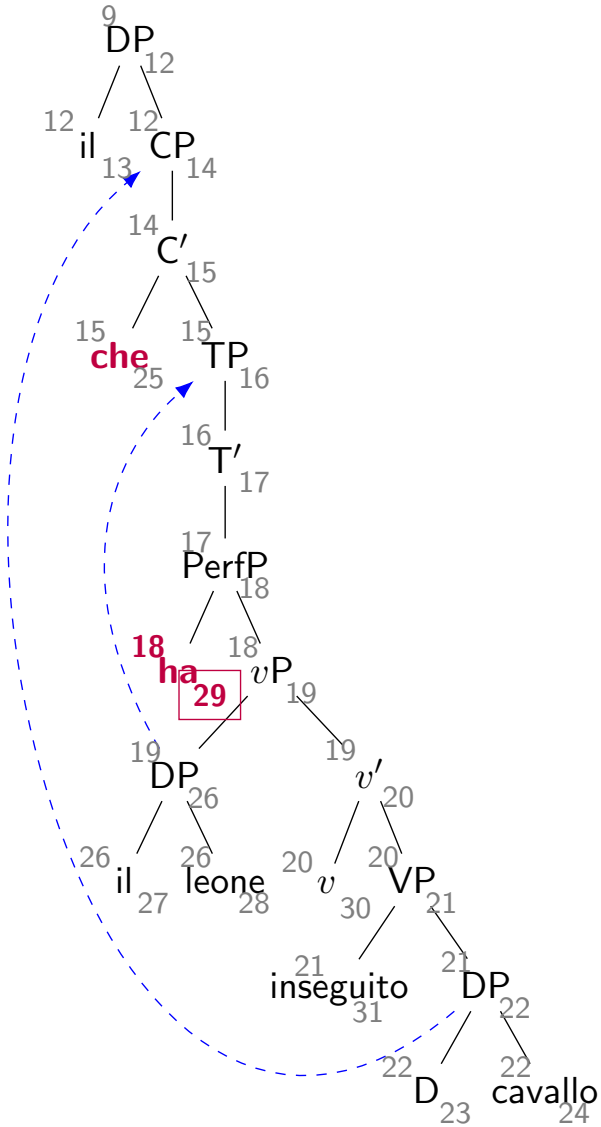

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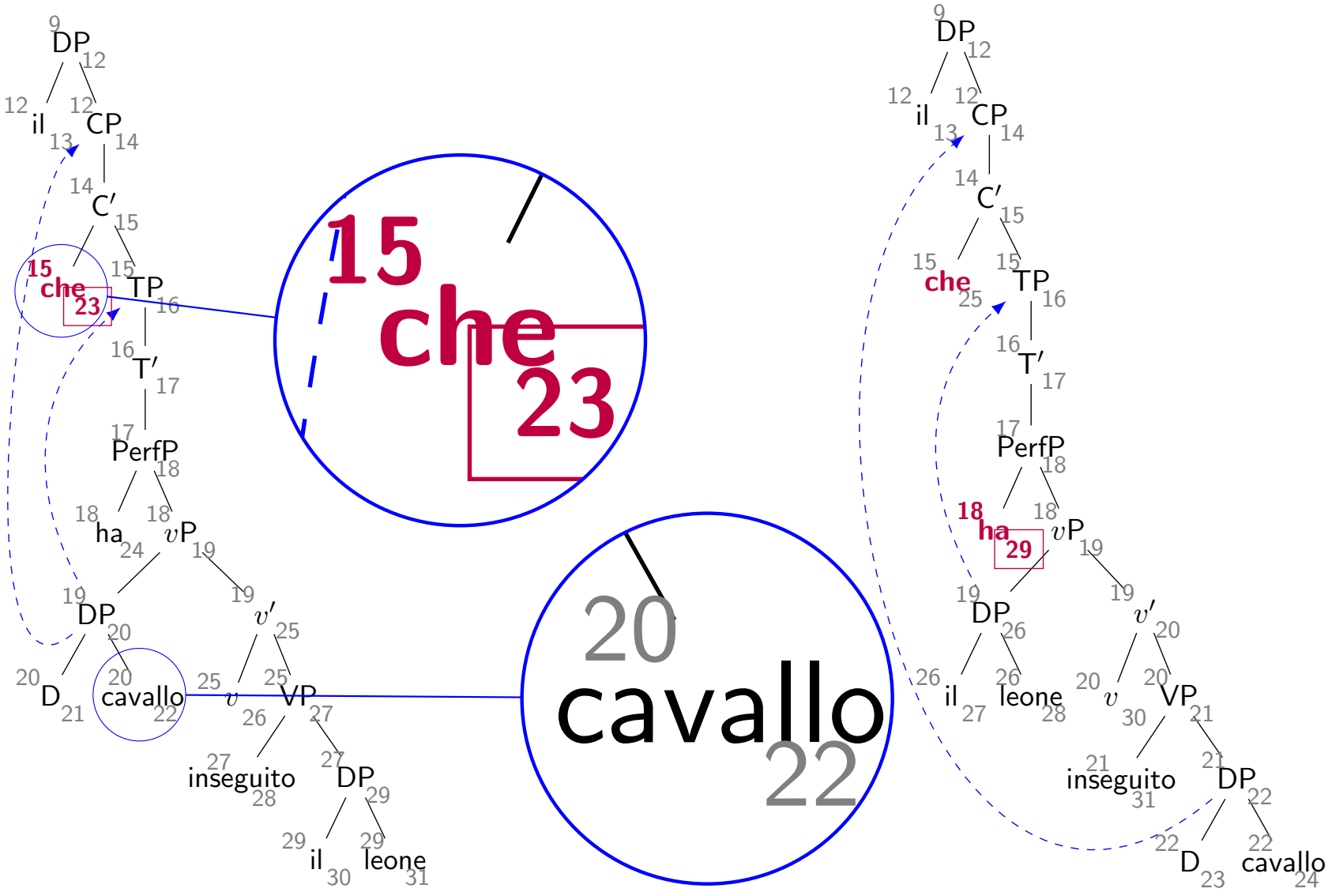

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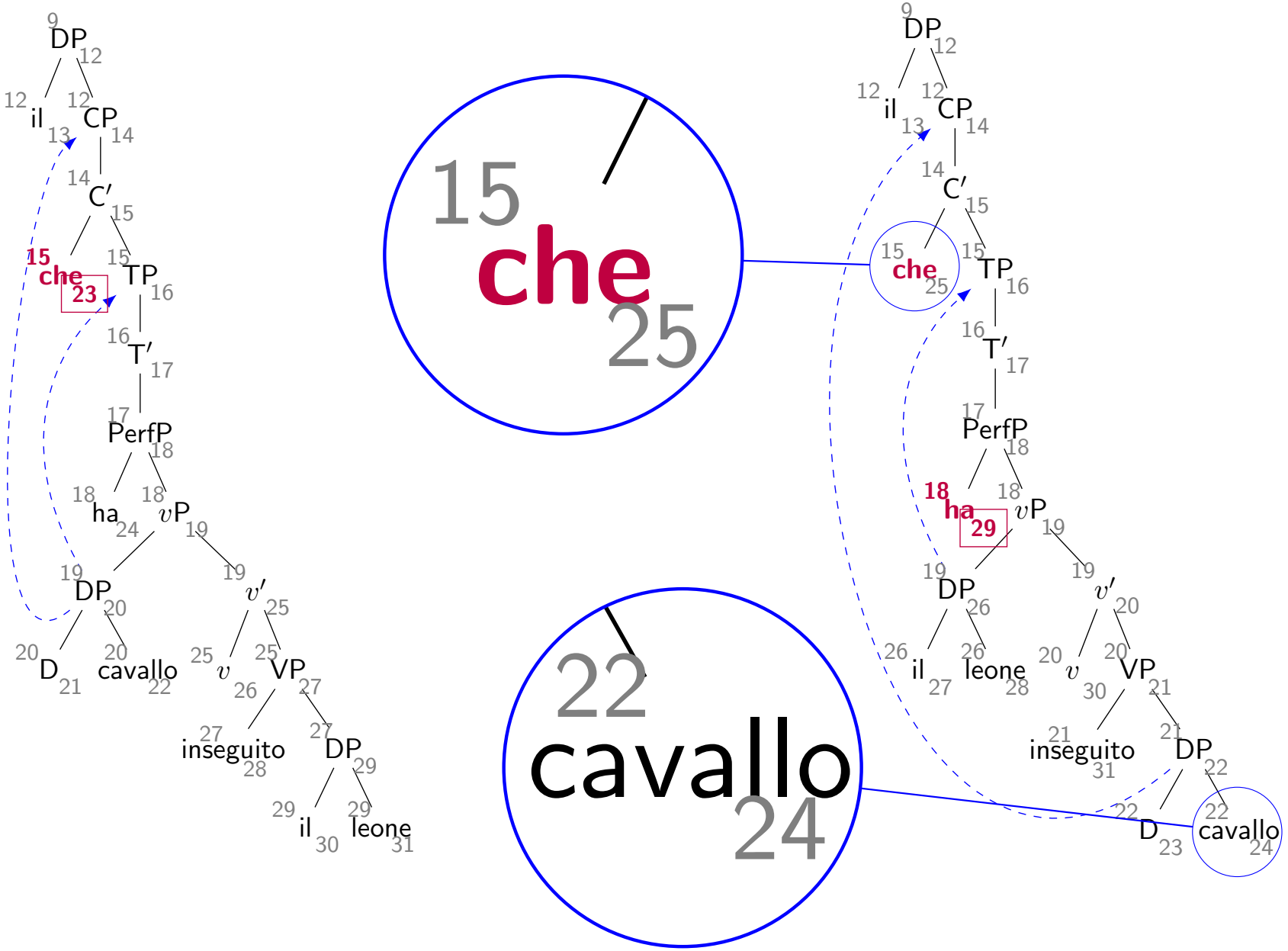

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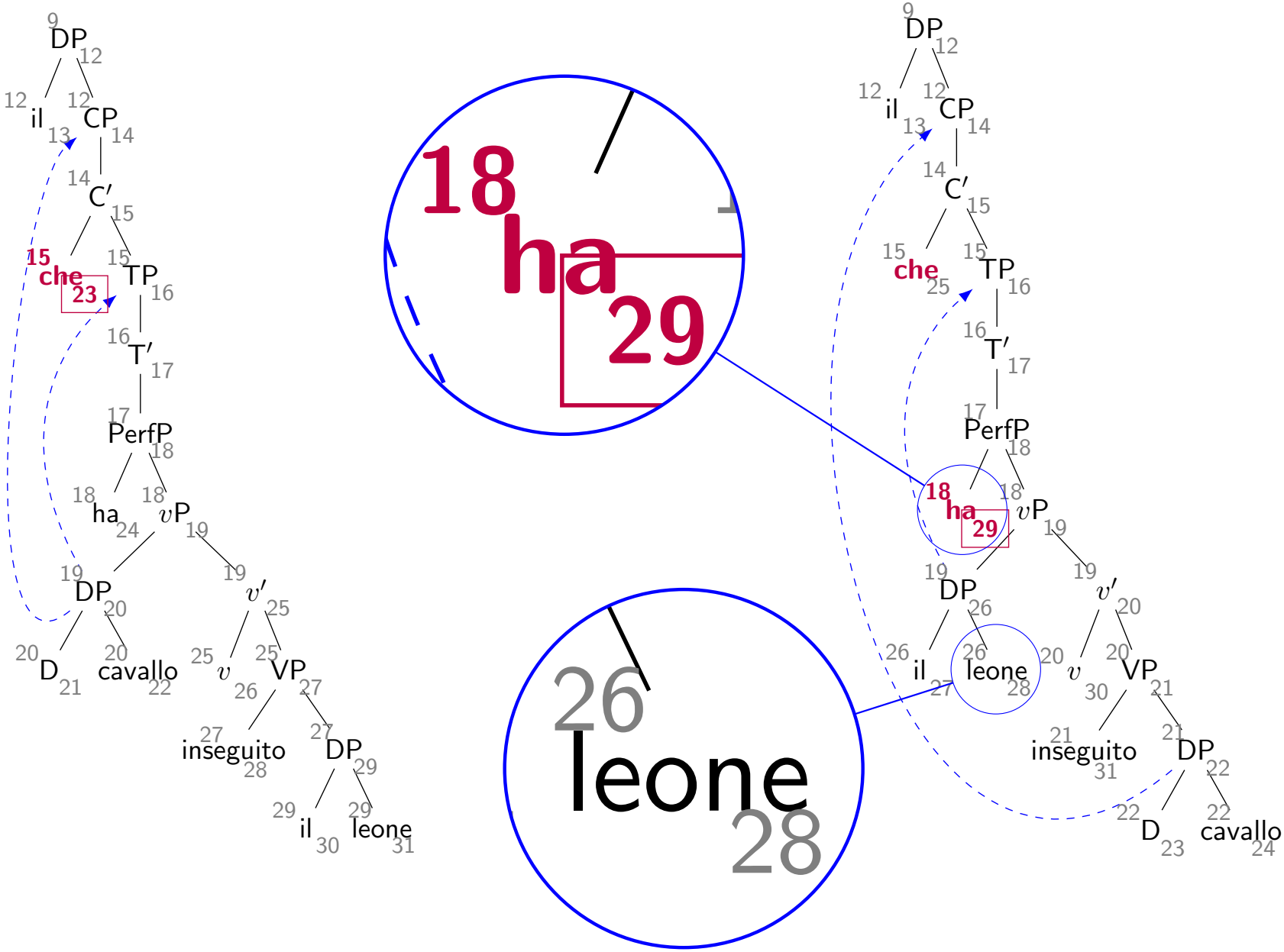

Summary of Results (De Santo 2019)

Clause Type	MaxTenure	SumSize
obj. SRC > ORC	✓	✓
obj. SRC > ORCp	✓	✓
obj. ORC > ORCp	✓	✓
subj. SRC > ORC	tie	✓
subj. SRC > ORCp	✓	✓
subj. ORC > ORCp	✓	✓
matrix SVO > VOS	✓	✓
VS unacc > VS unerg	✓	✓

Table: Predictions of the MG parser by metric and contrast.

Interim Summary

<MaxT,SumS> makes correct predictions cross-linguistically!

- Right < center embedding (Kobele et al. 2012)
- Crossing < nested dependencies (Kobele et al. 2012)
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Gradient Acceptability and Categorical Grammars

Acceptability judgments are not binary but *gradient*:

> *An adequate linguistic theory will have to recognize degrees of grammaticalness [...] there is little doubt that speakers can fairly consistently order new utterances, never previously heard, with respect to their degree of belongingness to the language.*
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Models of Gradience

(At least two) theories of gradience:

- gradience incorporated in the grammar
  (Keller 2000; Featherston 2005; Lau et al. 2014)
- gradience due to extra-grammatical factors
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But: these approaches aim to explain the same data!

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Quantify what each approach needs to account for the data:

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Gradient Grammars (Keller 2000; Lau et al. 2014)

- OT-style constraint ranking
- Probabilistic grammars

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- processing effects
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Hypothesis

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Modeling Gradience with an MG Parser

The model is the same as before

1. a formal model of syntax → Minimalist grammars (MGs)
2. a theory of how structures are built → MG parser
3. a linking theory: higher memory cost ⇒ lower acceptability

- sensitive to fine-grained structural differences!
- minimal, pairwise comparisons are maximally interpretable!

A proof-of-concept:

- variation of Island effects in English (Sprouse et al. 2012)

A Proof of Concept: Island Effects

1. What do you think that John bought *t*?
2. What do you wonder whether John bought *t*?

Gradience in Islands: Sprouse et al. (2012)

- A factorial design for islands effects:
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1. What do you think that John bought *t*? — Non-Island — Embedded
2. What do you wonder whether John bought *t*? — Island — Embedded
3. Who *t* thinks that John bought a car? — Non-Island — Matrix
4. Who *t* wonders whether John bought a car? — Island — Matrix

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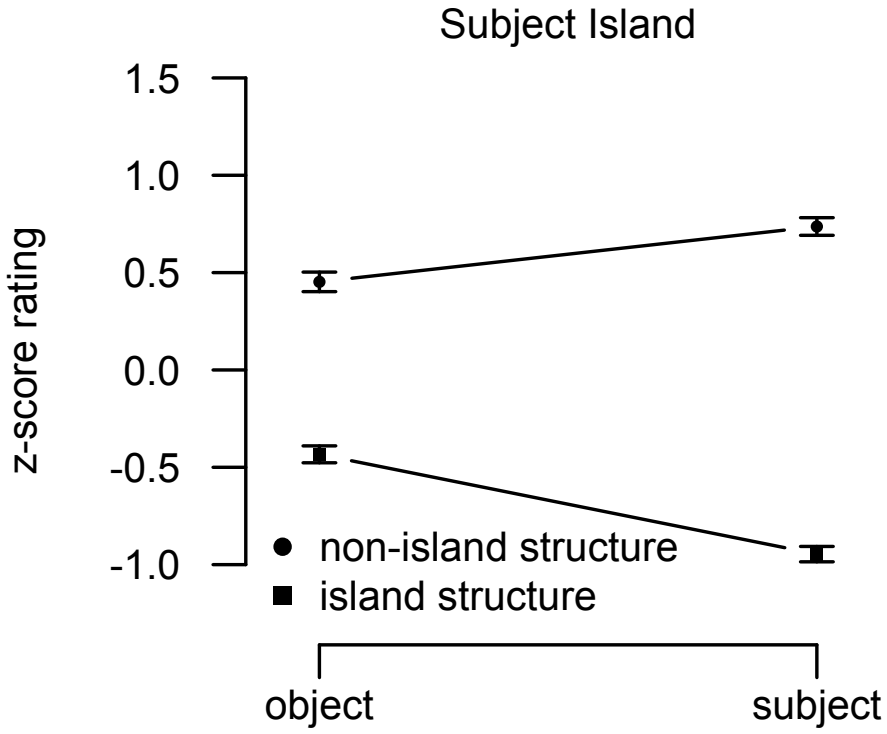
Deriving Pairwise Comparisons



- Subj — Non Island > Obj — Non Island
- Subj — Non Island > Obj — Island
- Subj — Non Island > Subj — Island
- etc.

Sprouse at al. (2012)

Four island types

Subject islands

- What do you think the speech about *t* interrupted the show about global warming?

Adjunct islands

- What do you laugh if John leaves *t* at the office?

Complex NP islands

- What did you make the claim that John bought *t*?

Whether islands

- What do you wonder whether John bought *t*?

Gap Position × Structure

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2. Island vs. Non-Island

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Modeling Results (De Santo 2020)

Island Type	Sprouse et al. (2012)			MG Parser
Subj. Island 1	Subj. — Non Isl.	>	Obj. — Non Isl.	✓
	Subj. — Non Isl.	>	Obj. — Isl.	✓
	Subj. — Non Isl.	>	Subj. — Isl.	✓
	Obj. — Non Isl.	>	Obj. — Isl.	✓
	Obj. — Non Isl.	>	Subj. — Isl.	✓
	Obj. — Isl.	>	Subj. — Isl.	×
Subj. Island 2	Matrix — Non Isl.	>	Emb. — Non Isl.	✓
	Matrix — Non Isl.	>	Matrix — Isl.	✓
	Matrix — Non Isl.	>	Emb. — Isl.	✓
	Matrix — Isl.	>	Emb. — Isl.	✓
	Matrix — Isl.	>	Matrix — Isl.	✓
	Emb. — Non Isl.	>	Emb. — Isl.	✓
Adj. Island	Matrix — Non Isl.	>	Emb. — Non Isl.	✓
	Matrix — Non Isl.	>	Matrix — Isl.	✓
	Matrix — Non Isl.	>	Emb. — Isl.	✓
	Matrix — Isl.	>	Emb. — Isl.	✓
	Matrix — Isl.	>	Matrix — Isl.	✓
	Emb. — Non Isl.	>	Emb. — Isl.	✓
CNP Island	Matrix — Non Isl.	>	Emb. — Non Isl.	✓
	Matrix — Non Isl.	=	Matrix — Isl.	✓
	Matrix — Non Isl.	>	Emb. — Isl.	✓
	Matrix — Isl.	>	Emb. — Isl.	✓
	Matrix — Isl.	>	Matrix — Isl.	✓
	Emb. — Non Isl.	>	Emb. — Isl.	✓

Modeling Results (De Santo 2020)

Island Type	Sprouse et al. (2012)			MG Parser
Subj. Island 1	Subj. — Non Isl.	>	Obj. — Non Isl.	✓
	Subj. — Non Isl.	>	Obj. — Isl.	✓
	Subj. — Non Isl.	>	Subj. — Isl.	✓
	Obj. — Non Isl.	>	Obj. — Isl.	✓
	Obj. — Non Isl.	>	Subj. — Isl.	✓
	Obj. — Isl.	>	**Subj. — Isl.**	×
Subj. Island 2	Matrix — Non Isl.	>	Emb. — Non Isl.	✓
	Matrix — Non Isl.	>	Matrix — Isl.	✓
	Matrix — Non Isl.	>	Emb. — Isl.	✓
	Matrix — Isl.	>	Emb. — Isl.	✓
	Matrix — Isl.	>	Matrix — Isl.	✓
	Emb. — Non Isl.	>	Emb. — Isl.	✓
Adj. Island	Matrix — Non Isl.	>	Emb. — Non Isl.	✓
	Matrix — Non Isl.	>	Matrix — Isl.	✓
	Matrix — Non Isl.	>	Emb. — Isl.	✓
	Matrix — Isl.	>	Emb. — Isl.	✓
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	Emb. — Non Isl.	>	Emb. — Isl.	✓
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	Matrix — Non Isl.	=	Matrix — Isl.	✓
	Matrix — Non Isl.	>	Emb. — Isl.	✓
	Matrix — Isl.	>	Emb. — Isl.	✓
	Matrix — Isl.	>	Matrix — Isl.	✓
	Emb. — Non Isl.	>	Emb. — Isl.	✓

TL;DR: **Success in all cases but one!**

Subject Island: Case 1

(5) a. What do you think the speech interrupted *t*? Obj — Non Island

b. What do you think *t* interrupted the show? Subj — Non Island

c. What do you think the speech about global warming interrupted the show about *t*? Obj — Island

d. What do you think the speech about *t* interrupted the show about global warming? Subj — Island

Sprouse et al. (2012)			MG Parser
Subj. — Non Isl.	>	Obj. — Non Isl.	✓
Subj. — Non Isl.	>	Obj. — Isl.	✓
Subj. — Non Isl.	>	Subj. — Isl.	✓
Obj. — Non Isl.	>	Obj. — Isl.	✓
Obj. — Non Isl.	>	Subj. — Isl.	✓
Obj. — Isl.	>	Subj. — Isl.	×

Clause Type	MaxT	SumS
Obj./Non Island	14/*do*	19
Subj./Non Island	11/*do*	14
Obj./Island	23/*T2*	22
Subj./Island	15/*do*	20

Subject Island: Case 1

(5) a. What do you think the speech interrupted *t*? Obj — Non Island

b. What do you think *t* interrupted the show? Subj — Non Island

c. What do you think the speech about global warming interrupted the show about *t*? Obj — Island

d. * What do you think the speech about *t* interrupted the show about global warming? Subj — Island

Sprouse et al. (2012)			MG Parser
Subj. — Non Isl.	>	Obj. — Non Isl.	✓
Subj. — Non Isl.	>	Obj. — Isl.	✓
Subj. — Non Isl.	>	Subj. — Isl.	✓
Obj. — Non Isl.	>	Obj. — Isl.	✓
Obj. — Non Isl.	>	Subj. — Isl.	✓
Obj. — Isl.	>	Subj. — Isl.	×

Clause Type	MaxT	SumS
Obj./Non Island	14/*do*	19
Subj./Non Island	11/*do*	14
Obj./Island	23/*T2*	22
Subj./Island	15/*do*	20

Subject Island: Case 2

(6) a. Who *t* thinks the speech interrupted the primetime TV show?
Matrix — Non Island

b. What do you think *t* interrupted the primetime TV show?
Emb. — Non Island

c. Who *t* thinks the speech about global warming interrupted the primetime TV show?
Matrix — Island

d. What do you think the speech about *t* interrupted the primetime TV show?
Emb. — Island

Sprouse et al. (2012)			MG Parser
Matrix — Non Isl.	>	Emb. — Non Isl.	✓
Matrix — Non Isl.	>	Matrix — Isl.	✓
Matrix — Non Isl.	>	Emb. — Isl.	✓
Matrix — Isl.	>	Emb. — Isl.	✓
Matrix — Isl.	>	Matrix — Isl.	✓
Emb. — Non Isl.	>	Emb. — Isl.	✓

Clause Type	MaxT	SumS
Matrix — Non Isl.	$5/C$	9
Emb. — Non Isl.	$11/do$	14
Matrix — Isl.	$11/T_{RC}$	9
Emb. — Isl.	$17/T_{RC}$	20

Summary

Gradience from a categorical MG grammars?

Modeling gradience in island effects:

- Overall, a success!
- Outlier is expected assuming grammaticalized constraints.

Preliminary results!

- Modulate range of dependencies.
- Other examples of gradience
- Cognitive vs. grammatical constraints?
  (Ferrara-Boston 2012; Wilcox et al. 2018)

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Summing Up

Minimalist Parsing

A *maximally simple* parsing model that derives processing effects purely from memory usage.

- fully specified parsing model allows for precise predictions
- tight connection with current generative syntax
- successful on a variety of cross-linguistic constructions
- also derives theoretical insights (Kobele et al. 2012)
  - gradience
  - comparative analyses (De Santo & Shafiei 2019)

From the Trees to the Forest

Cognitive Plausibility

- Tenure & Size compatible with a variety of theories
  $\Rightarrow$ storage, decay, ...

Extending the Model

- What about features?
  - intervention effects
  - structural recall
  - ...
- Bringing back beam search
  (Torr 2018; Torr et al. 2019; Hunter et al. 2019)

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<Thank you!>

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Appendix

Why MGs?

1. Vast analytical coverage
   - MGs handle virtually all analyses in the generative literature
2. Centrality of derivation trees
   - MGs can be viewed as CFGs with a more complicated mapping from trees to strings
3. Simple parsing algorithms
   - Variant of a recursive descent parser for CFGs
     $\Rightarrow$ cf. TAG (Rambow & Joshi, 1995; Demberg, 2008)

Why These Metrics?

- These complexity metrics are all related to **storage cost** (cf. Gibson, 1998)
- We could implement alternative ones (cf. Ferrara-Boston, 2012)
  - number of bounding nodes / phases
  - surprisal
  - feature intervention
  - status of discourse referents
  - integration, retrieval, ...
- We want to keep the model **simple** (but not **trivial**):
  - Tenure and Size only refer to the geometry of the derivation
  - they are sensitive the specifics of tree-traversal (cf. node-count; Hale, 2001)

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Italian Subjects: Probing the Results

Clause Type	MaxT	SumS
obj. SRC	8/*che*	18
obj. ORC	11/*ha*	24
obj. ORCp	16/*Foc*	31
subj. SRC	21/v'	37
subj. ORC	21/v'	44
subj. ORCp	28/v'	56
matrix SVO	3/*ha*/v'	7
matrix VOS	7/*Top*/*Foc*	11
VS unacc	2/vP	3
VS unerg	7/*Top*/*Foc*	11

Table: Summary of MaxT (*value*/*node*) and SumS by construction. Obj. and subj. indicate the landing site of the RC head in the matrix clause.

Postverbal Asymmetries: Possible Accounts?

SRC > ORC

- DLT, active-filler strategy, Competition model, ...

ORC > ORCp

- more problematic (e.g., for DLT)
- can be explained by
  1. economy of gap prediction + structural re-analysis;
  2. intervention effects + featural Relativized Minimality

Can we give a purely structural account?

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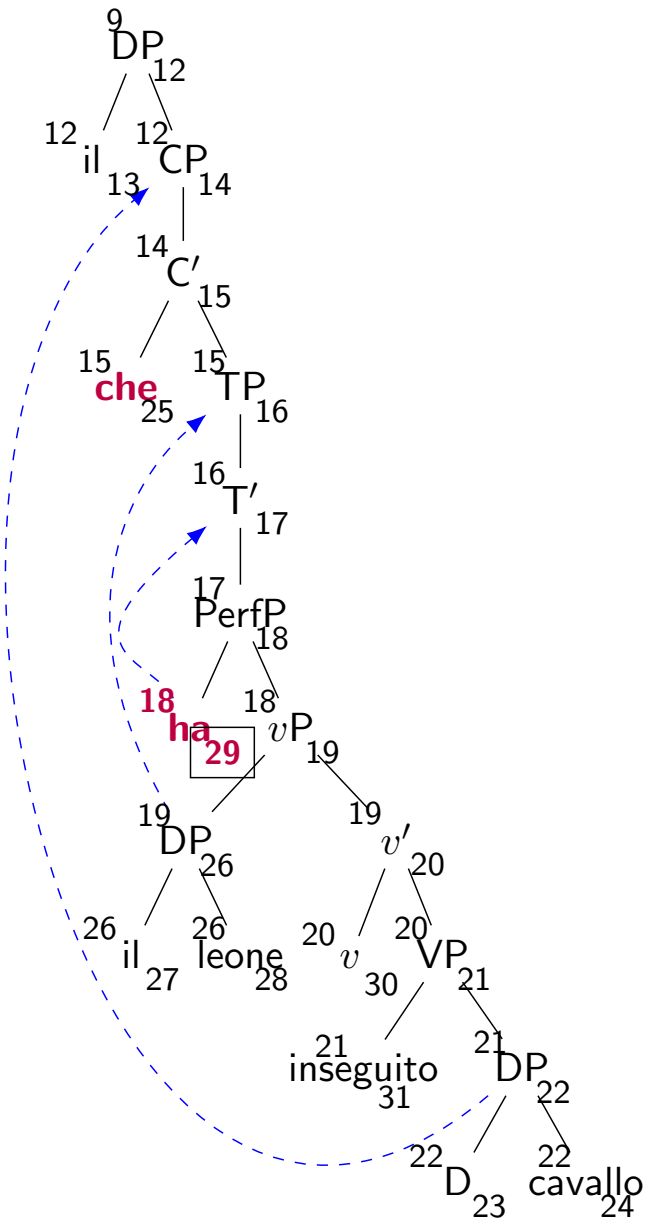
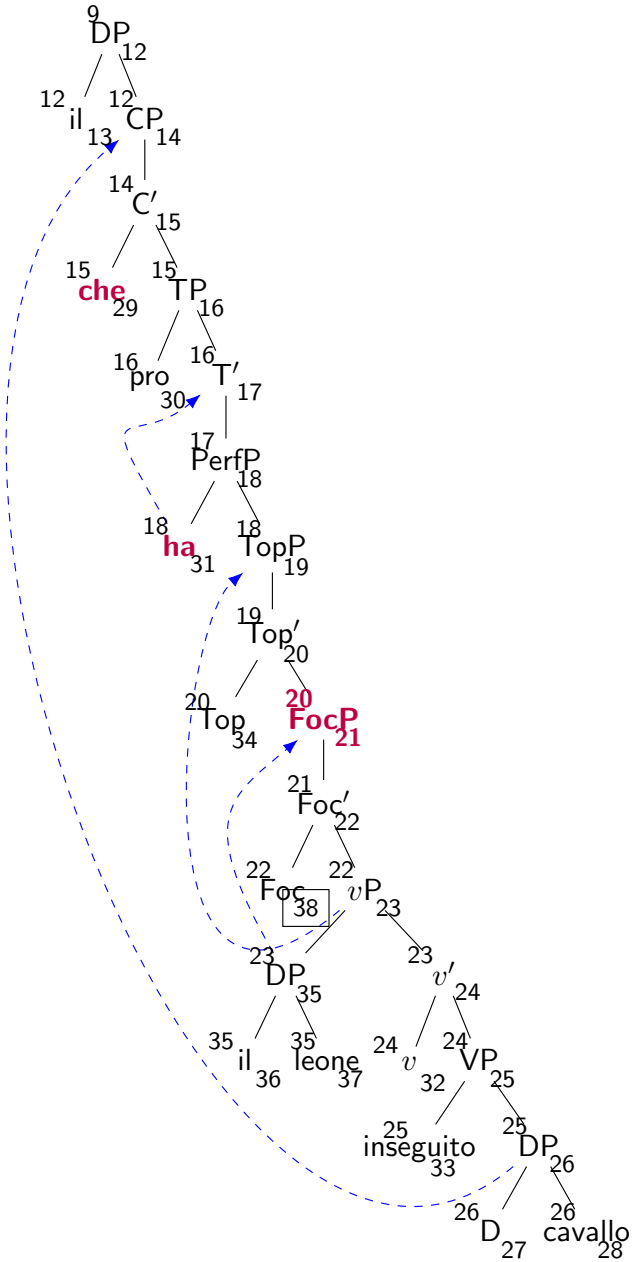
Results: ORC > ORCp





Additional Constructions

- Ambiguity in Matrix Clauses

(7) Ha chiamato Gio
Has called Giovanni

a. "He/she/it called Gio" **SVO**

b. "Gio called" **VS**

- Unaccusatives vs. Unergatives

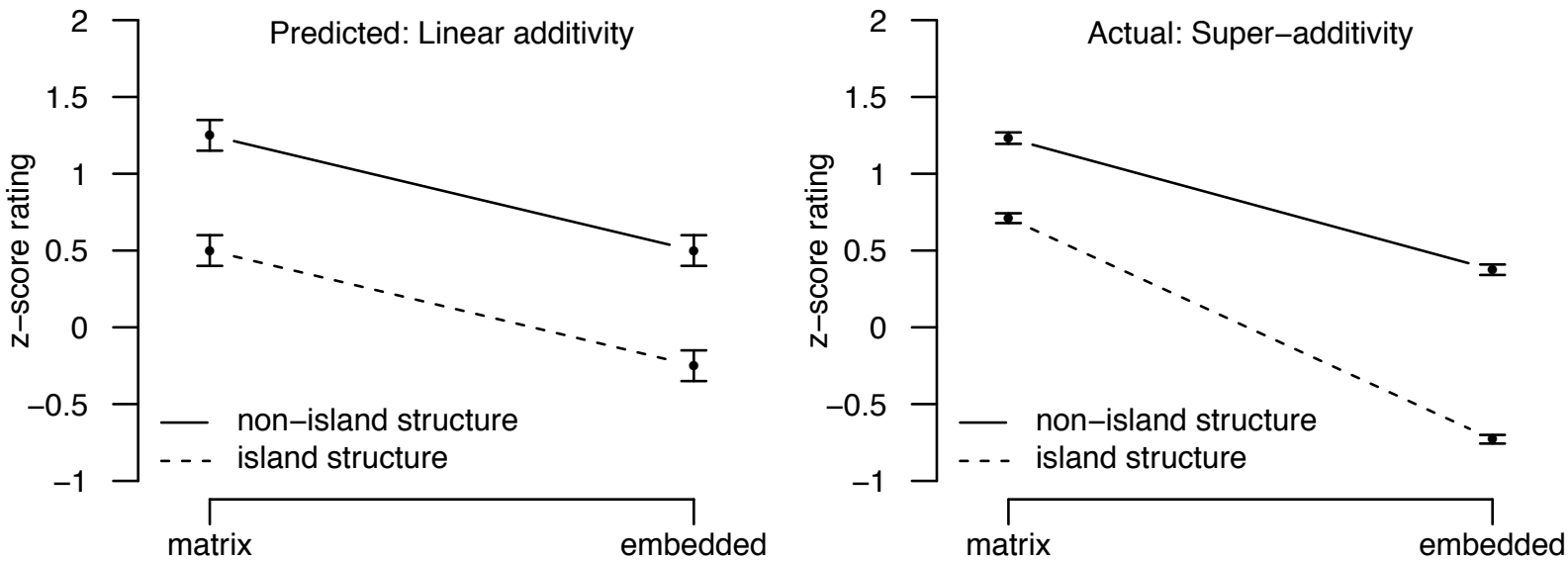
(8) È arrivato Gio
Is arrived Gio
"Gio arrived" **Unaccusative**

(9) Ha corso Gio
Has ran Gio
"Gio ran" **Unergative**

Gradience in Islands

A factorial design for islands effect:

- Gap Position × Structure



A Caveat on Island Effects

The Goal

Can gradience in acceptability judgments arise from a categorical grammar due to processing factors?

- Sprouse et al.'s (2012) design is ideal for the MG model.

But I am not interested in island effects per se:

- Islands: grammatical or processing effects?
  (Hofmeister et al., 2012a; Sprouse et al., 2012a,b)
  - hence, not modeling super-additivity
  - spoilers: maybe we get some insights?
- Islands: syntax or semantics?
  (Truswell, 2011; Kush et al., 2018; Matchin et al., 2018)

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Technical Fertility of Derivation Trees

Derivation trees made it easy for MGs to accommodate the full syntactic toolbox:

- sidewards movement (Stabler, 2006; Graf 2013)
- affix hopping (Graf 2012; Graf2013)
- clustering movement (Gartner & Michaelis 2010)
- tucking in (Graf 2013)
- ATB movement (Kobele 2008)
- copy movement (Kobele 2006)
- extraposition (Hunter &Frank 2014)
- Late Merge (Kobele 2010; Graf 2014)
- Agree (Kobele 2011; Graf 2011)
- adjunction (Fowlie 2013; Hunter 2015)
- TAG-style adjunction (Graf 2012)

Implementation

Current Implementation available on **Github**. Salem

Allows to

- automatically compare MG derivation trees over a set of complexity metrics
- easily extendable with new metrics
- integrated with LaTeX

Main issues:

1. memory usage grows very fast with the number of metrics
2. tied to a specific parsing algorithm

Subject Islands

Case 1:

(10)
a. What do you think the speech interrupted *t*? Obj — Non Island
b. What do you think *t* interrupted the show? Subj — Non Island
c. What do you think the speech about global warming interrupted the show about *t*? Obj — Island
d. What do you think the speech about *t* interrupted the show about global warming? Subj — Island

Case 2:

(11)
a. Who *t* thinks the speech interrupted the primetime TV show? Matrix — Non Island
b. What do you think *t* interrupted the primetime TV show? Emb. — Non Island
c. Who *t* thinks the speech about global warming interrupted the primetime TV show? Matrix — Island
d. What do you think the speech about *t* interrupted the primetime TV show? Emb. — Island