Memory Usage as a Measure of Structural Complexity in Minimalist Parsing

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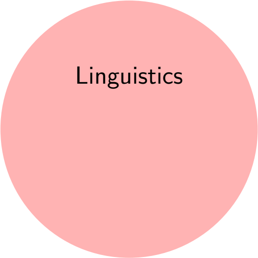
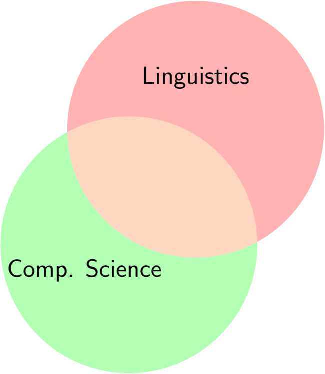
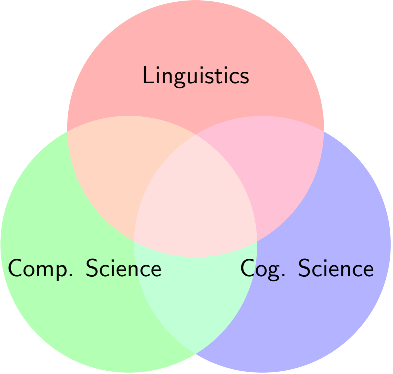
University of Utah
Jan 14, 2020


Linguistics


Linguistics
Comp. Science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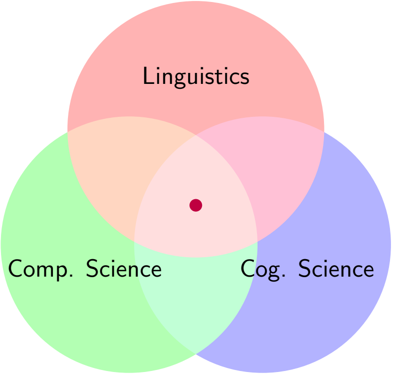
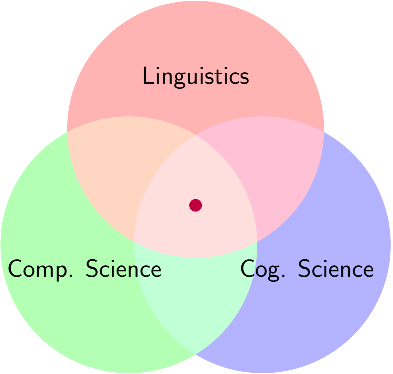


- Modeling processing difficulty (De Santo 2019, De Santo in prep.)
- Cross-linguistic variation (De Santo & Shafiei 2019, De Santo & Zhang in prep.)
- Gradience in acceptability judgments (De Santo 2020)
- Computational parallels across linguistic modules (Aksenova & De Santo 2017, De Santo & Graf 2019)
- Constraints in acquisition (De Santo 2018, Graf & De Santo 2020)
- Animal Cognition (De Santo & Rawski, to appear)



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Let's Start with a Puzzle!

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. 2018)

(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**

SRC > 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
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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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Processing Asymmetry (De Vincenzi 1991, Arosio et al. 2018, a.o.)

SRC $>$ **ORC** $>$ **ORCp**

One Big Questions

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

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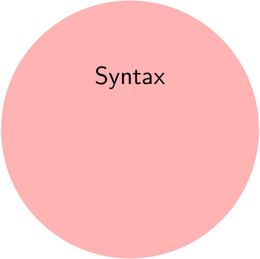

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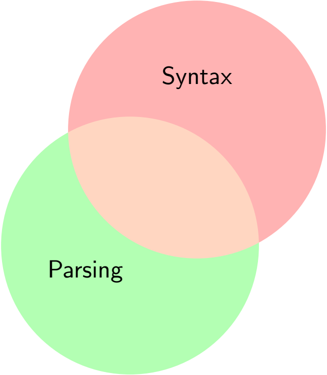

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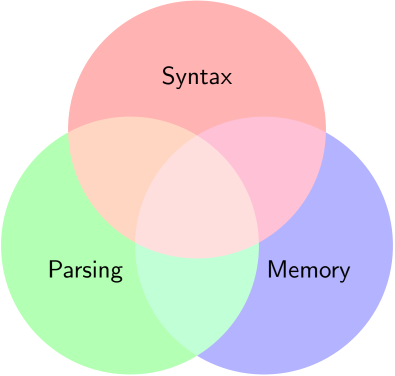

Forward to the Past

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

Derivational Theory of Complexity (Miller and Chomsky, 1963)

- Processing complexity $\sim$ 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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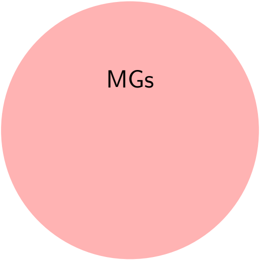
A Formal Model of Sentence Processing



1. An explicit syntactic theory → Minimalist grammars (MGs)

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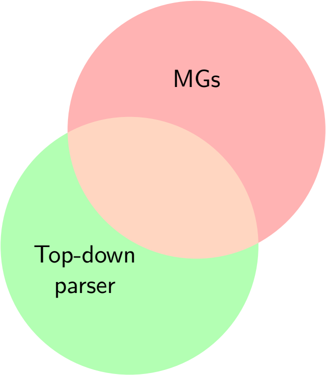

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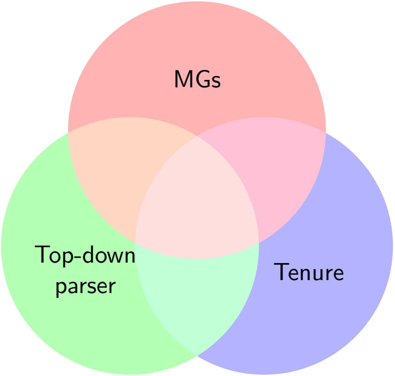

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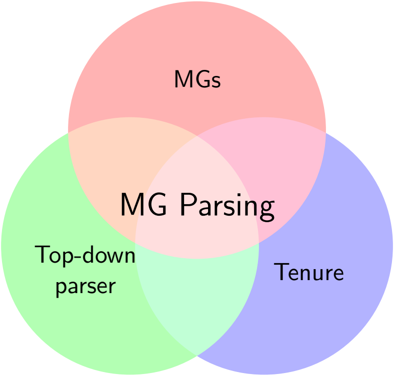

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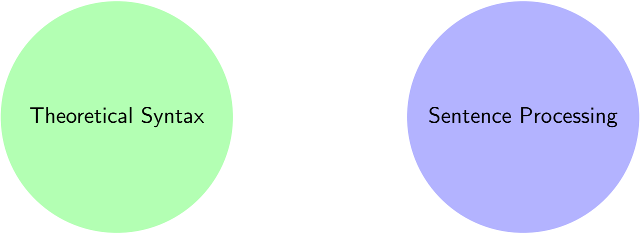
If you want to understand it, you can understand it!

Building Bridges



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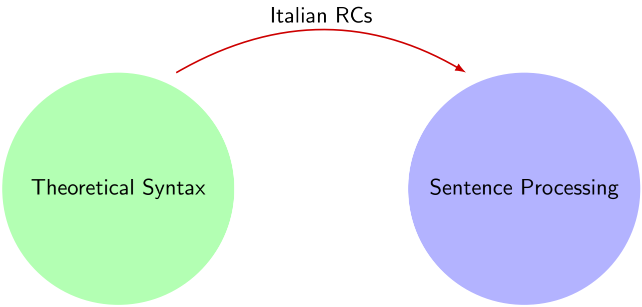

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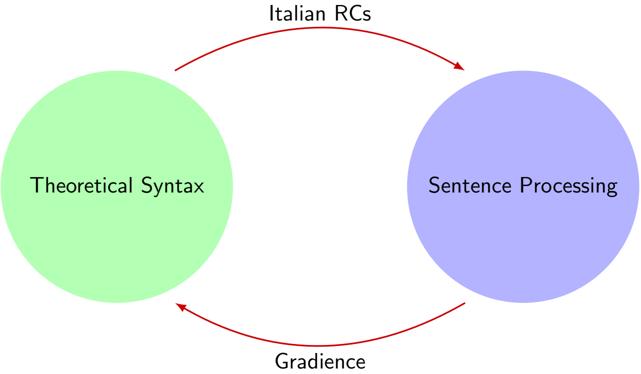


Outline

Minimalist Grammars (MGs)

We need an explicit model of syntactic structures...

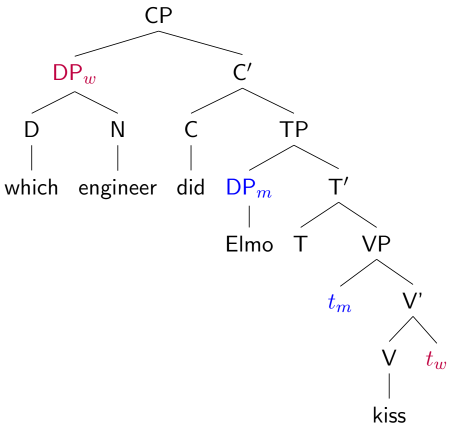
Ed Stabler

- Minimalist grammars (**MGs**): a formalization of Chomskyan syntax (Chomsky 1995; Stabler 1997)

Technical details!

- Weakly equivalent to MCFGs
- Essentially: CFGs with a more complicated mapping from trees to strings

MG Syntax: Derivation Trees



Phrase Structure Tree

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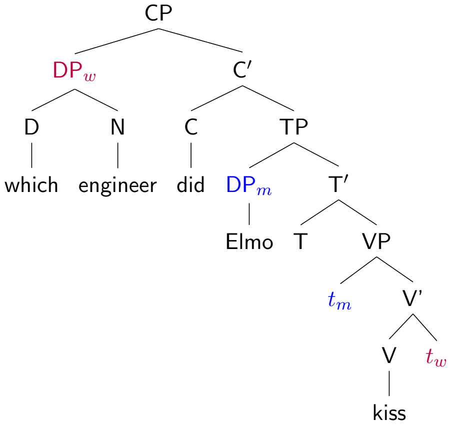

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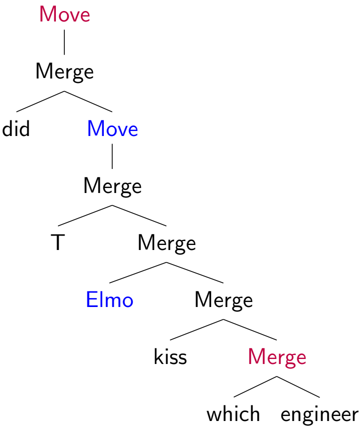

Derivation Tree

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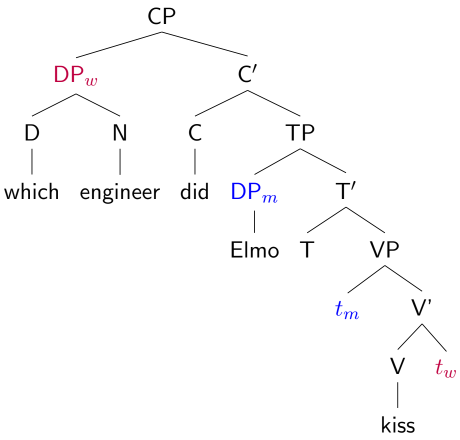

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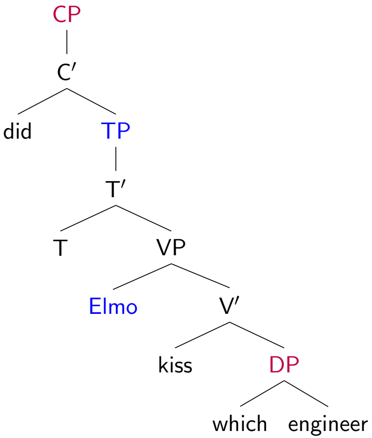
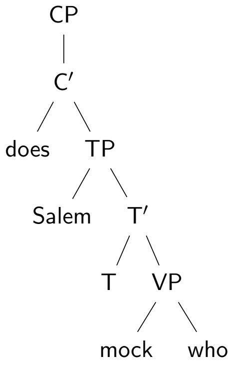


Derivation Tree

The Job of a Parser

Who does Salem mock?



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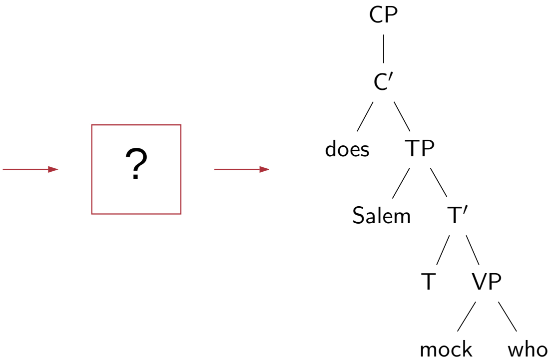

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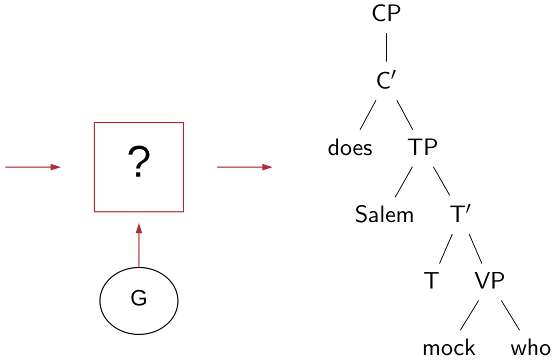

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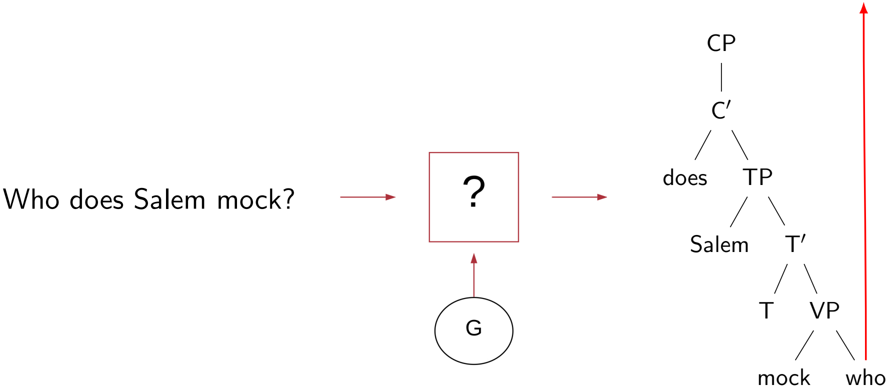
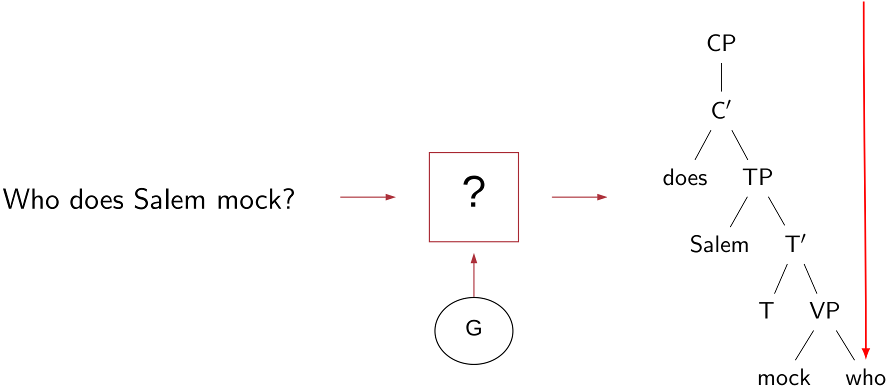


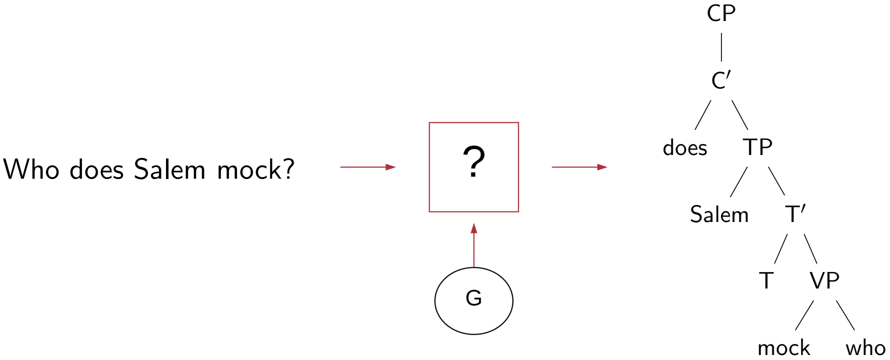
- Bottom-up

The Job of a Parser



- Bottom-up
- Top-down

The Job of a Parser



- Bottom-up
- Top-down
  - Psychologically plausible
  - We can build bottom-up grammars top-down!

Top-Down Parsing: The Intuition

Who does Salem mock?

Top-Down Parsing: The Intuition

CP

Who does Salem mock?

- Builds the structure from top to bottom
- Takes elements in an out of memory
- Complexity of the structure ≈ how much memory is used!

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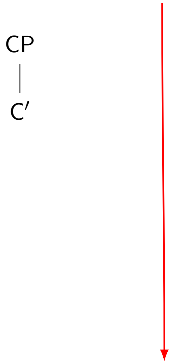

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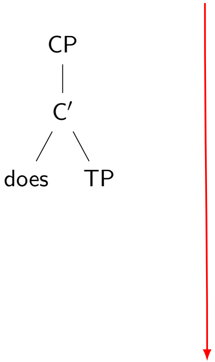

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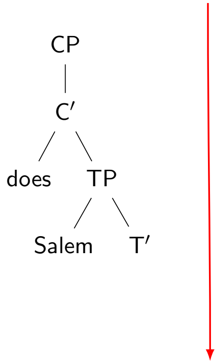

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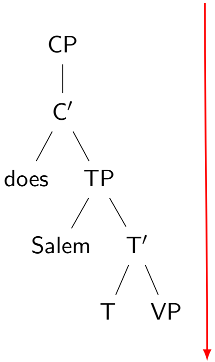

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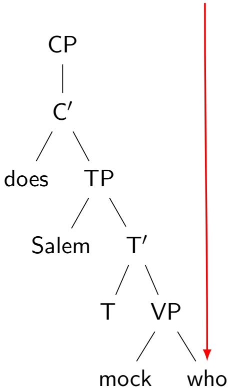

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Incremental Top-Down Parsing

Technical details!

- String-driven recursive descent parser (Stabler 2013)

- • 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
step 6	VP expands to mock and who
step 7	who is found
step 8	does is found
step 9	Salem is found
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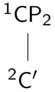

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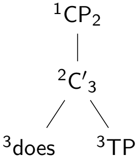

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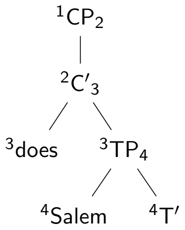

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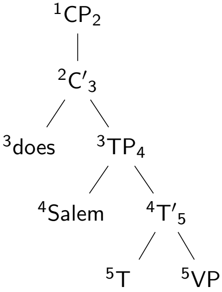

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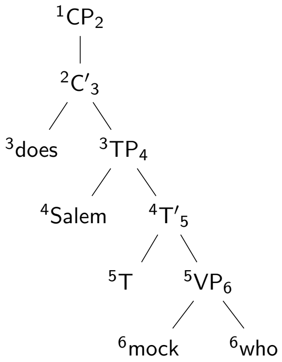

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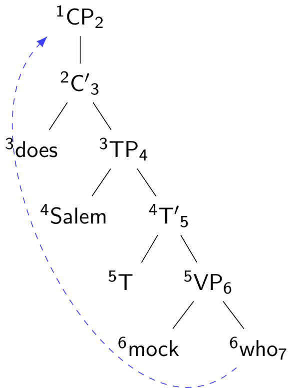

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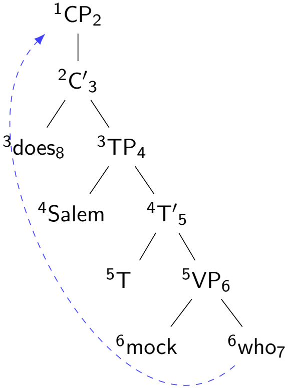

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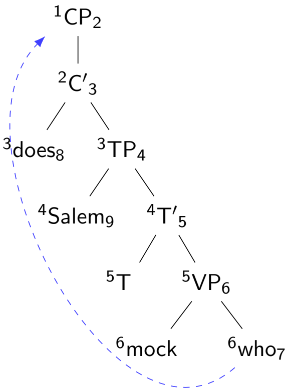

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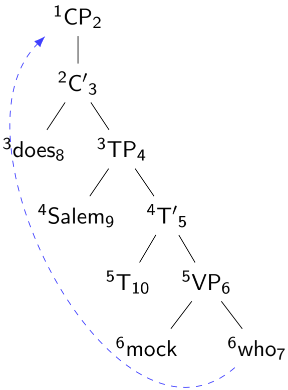

Incremental Top-Down Parsing

Technical details!

- String-driven recursive descent parser (Stabler 2013)

- • Who • does • Salem • T • mock

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step 5	*T'* expands to *T* and *VP*
step 6	*VP* expands to *mock* and *who*
step 7	*who* is found
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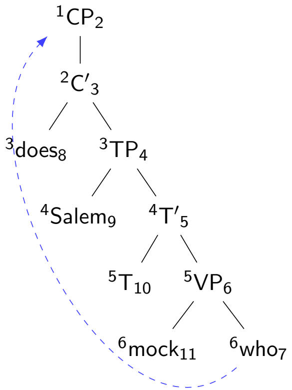

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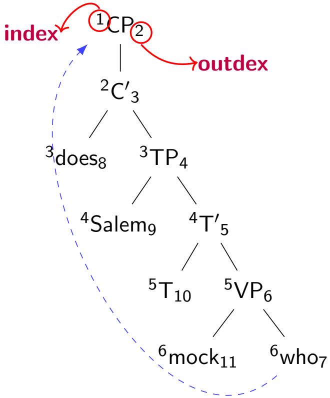

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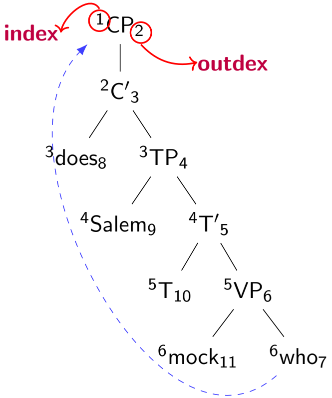

Index and Outdex are our connection to memory!

Memory-Based Complexity Metrics

- **Memory usage** (Kobele et al. 2012):

Tenure How long a node is kept in memory
Size How much information is stored in a node
$\Rightarrow$ Intuitively, the length of its movement dependency!

- These can be formalized into **complexity metrics**

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

Greg Kobele

Sabrina Gerth

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Processing Asymmetries All the Way Down

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

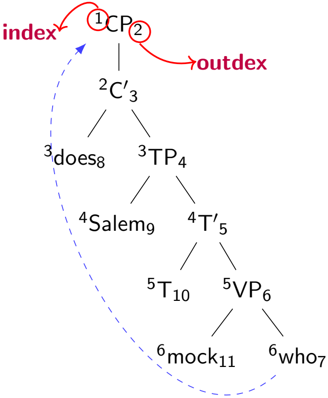
Across Many Constructions

- 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)
- Postverbal subjects in Italian (De Santo 2019)
- Persian attachment ambiguities (De Santo & Shafiei 2019)
- Gradient acceptability (De Santo 2020)

Across Languages

- English, German, Italian
- Korean, Japanese
- Mandarin Chinese
- Persian

Computing Metrics: An Example



Tenure how long a node is kept in memory

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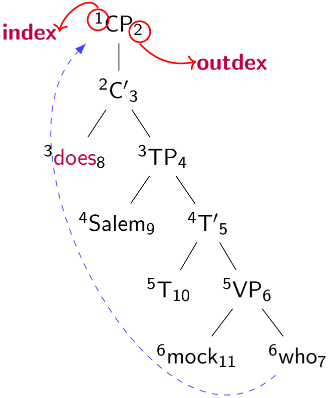

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Tenure($does$**)** $= 8 - 3 = 5$

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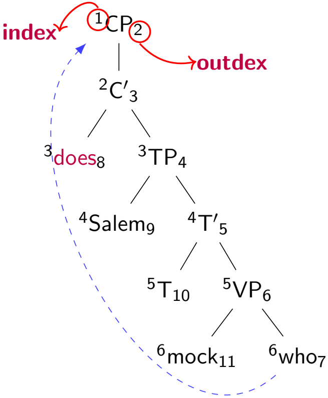
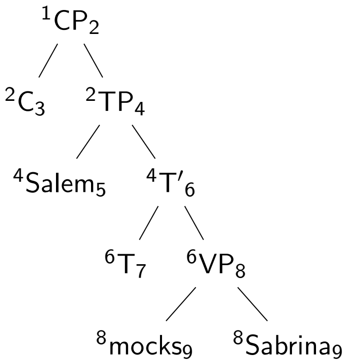


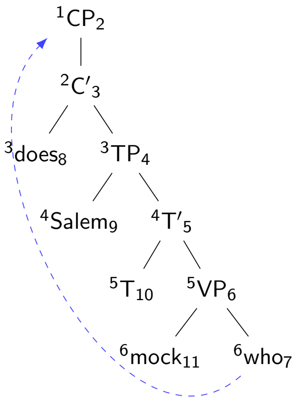
Tenure how long a node is kept in memory
Tenure($does$**)** $= 8 - 3 = 5$
MaxTenure $= max\{$**Tenure**$(does)$, **Tenure**$(Salem), \dots\} = 5$

Contrasting Derivations

MaxTenure $= 2$



MaxTenure $= 5$



Automatizing Helps!

mgproc: A Python Package for MG Processing Research

This is a collection of Python3 scripts to facilitate the investigation of human processing from the perspective of Minimalist grammars (MGs).

Background

MGs were developed in Stabler (1997) as a formalization of Chomsky's Minimalist program. A top-down parser for MGs is defined in Stabler (2013) and has been implemented in a number of languages. A number of subsequent works have successfully used this parser to make predictions about relative difficulty in sentence processing. Good starting points with a review of the previous literature are Gerth (2015) and Graf et al. (to appear).

- Gerth, Sabrina: Memory Limitations in Sentence Comprehension
- Graf, Thomas, James Monette, and Chong Zhang (to appear): Relative Clauses as a Benchmark for Minimalist Parsing (link to be added soon)
- Stabler, Edward (1997): Derivational Minimalism
- Stabler, Edward (2013): Two Models of Minimalist, Incremental Syntactic Analysis

Quick Start Guide

With *mgproc* you can easily compare MG derivation trees with respect to thousands of complexity m processing. The scripts integrate well with a LaTeX-centric workflow, following the ideal of OpenScie publication form a cohesive unit. Usually a parsed derivation tree is specified by four files. Assuming `foo`, we have:

- Open source ⇒ in prep. for *Journal of Open Source Software*
- User-friendly!
- Easy to modify!

Summary of the Approach

General Idea

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

1. Pick two competing derivations
2. Evaluate metrics over each
   - Lowest score means easiest!
3. Compare parser's prediction to experimental data

Remember!

If you want to understand it, you can understand it!

Reminder: Asymmetries in Italian Relative Clauses

(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
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"The horse that the lions chased" **ORC**

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Processing Asymmetry (De Vincenzi 1991, Arosio et al. 2018, a.o.)

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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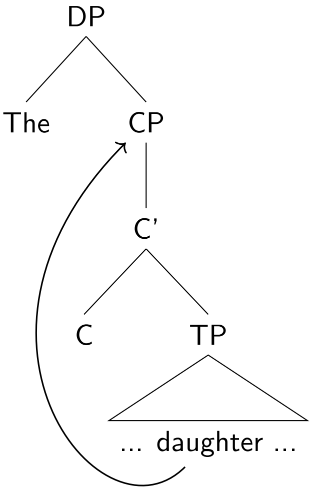
Kayne's Promotion Analysis (Kayne 1994)



- 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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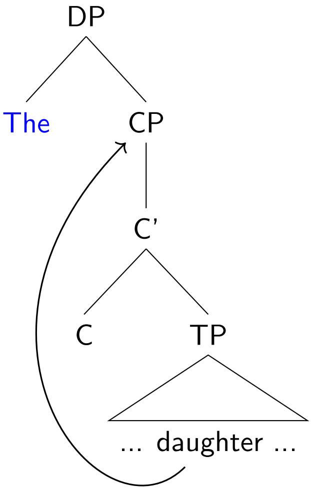

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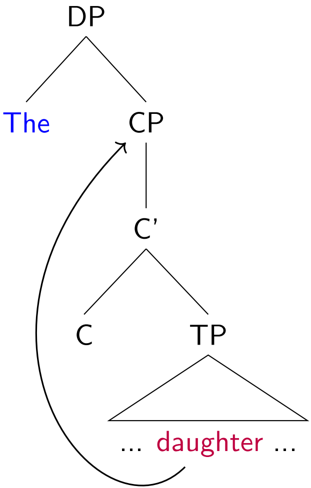

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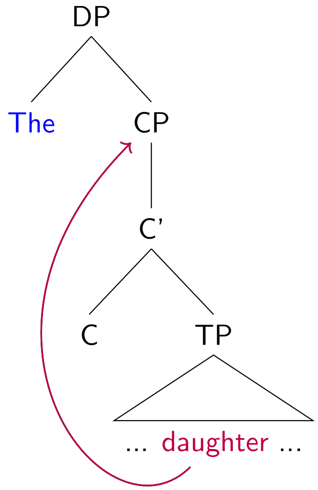

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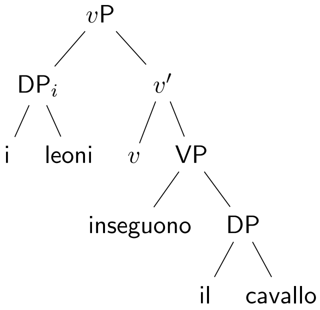
Postverbal Subjects (Belletti & Leonini 2004)

(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

Technical details!

- an expletive *pro* is base generated in Spec,TP



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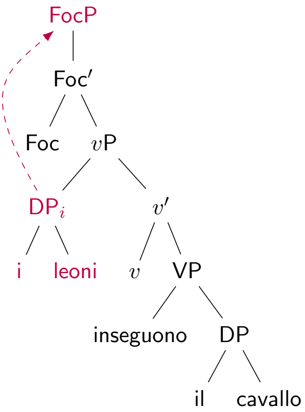

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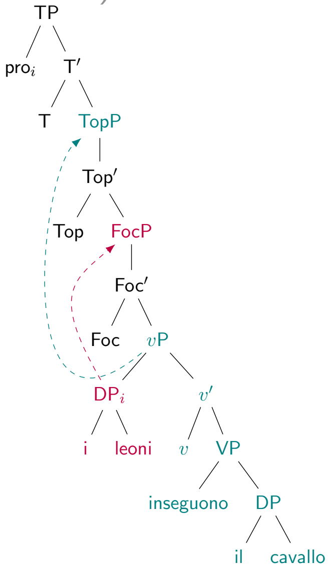

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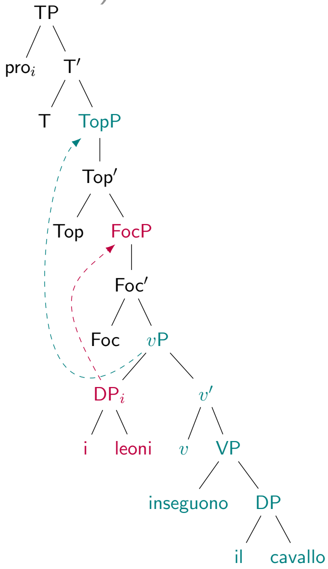

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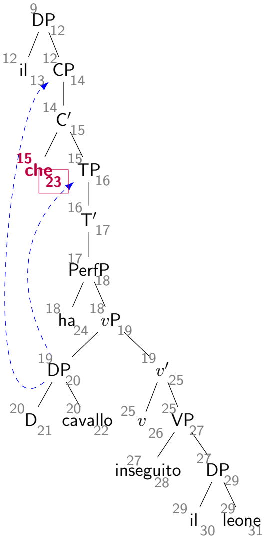
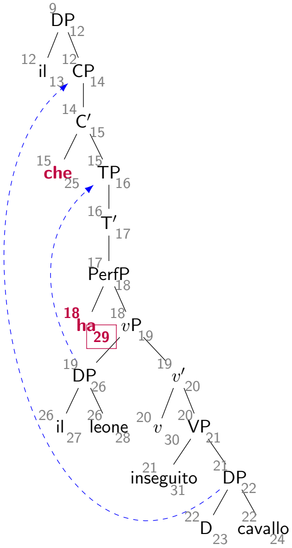
Results: SRC > ORC





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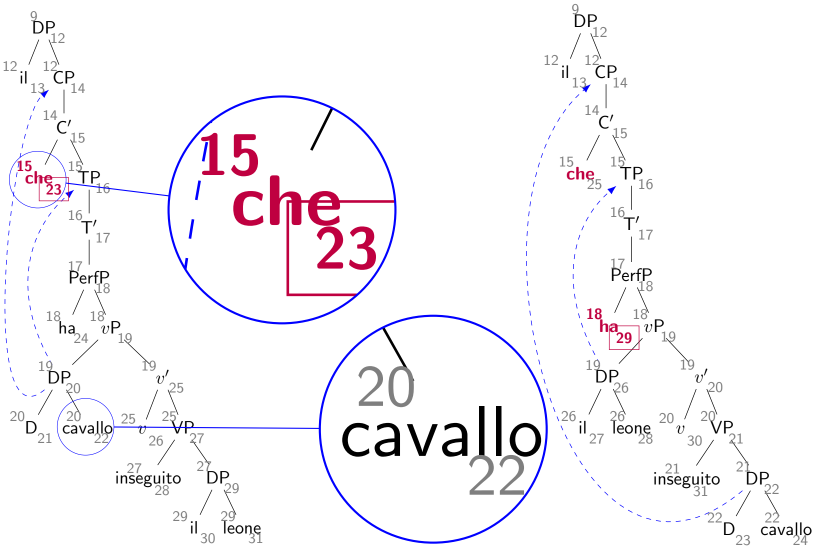

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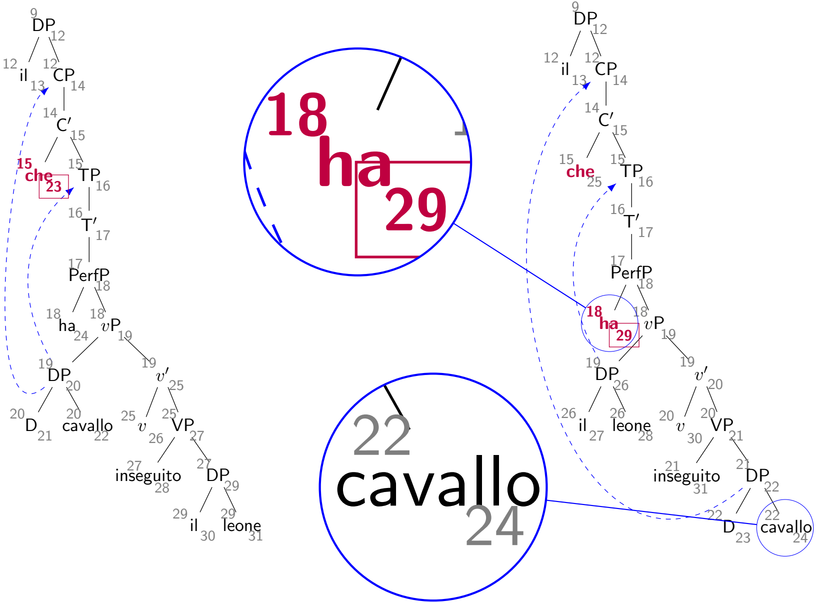

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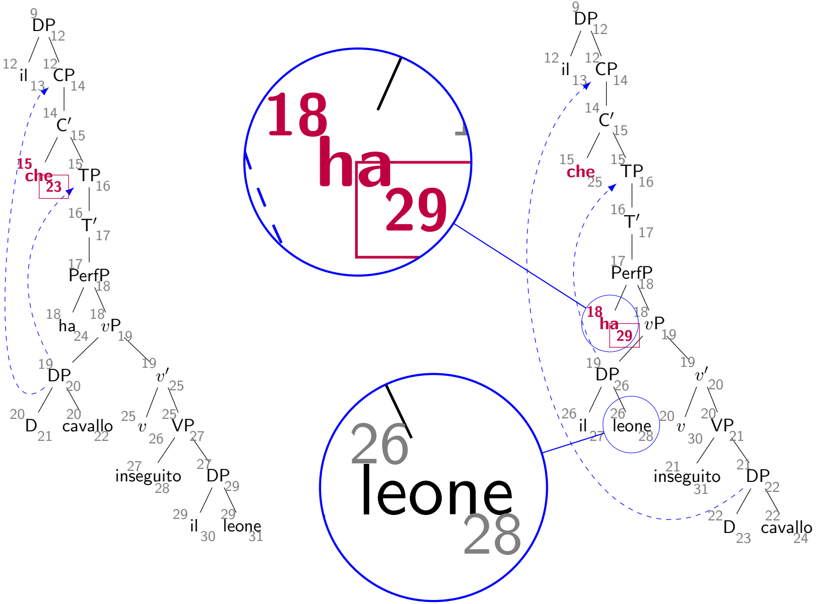


Summary of Results (De Santo 2019)

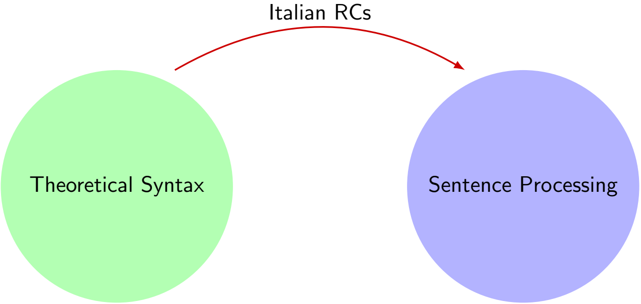
Clause Type	<MaxTenure,SumSize>
obj. SRC > ORC	✓
obj. SRC > ORCp	✓
obj. ORC > ORCp	✓
subj. SRC > ORC	✓
subj. SRC > ORCp	✓
subj. ORC > ORCp	✓
matrix SVO > VOS	✓
VS unacc > VS unerg	✓

Table: Predictions of the MG parser by contrast.

Interim Summary

- Asymmetries in Italian postverbal subject constructions
  - Derived just from **(fine-grained) structural differences**!
  - **Ongoing**: expand range of syntactic analyses;
  - **Ongoing**: cross-linguistic comparisons.
- <MaxT,SumS> gives consistent results!
  - Right vs. center embedding, attachment ambiguities, relative clause preferences
  - English, German, Korean, Japanese, Persian, Mandarin Chinese
  - More?

Moving on



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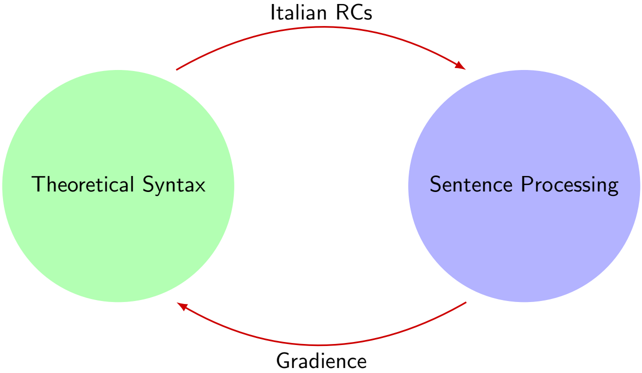
Italian RCs
Theoretical Syntax
Sentence Processing
Gradience

Acceptability and Grammaticality

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Acceptability judgments ≈ Grammaticality judgments

Gradience in Acceptability Judgments

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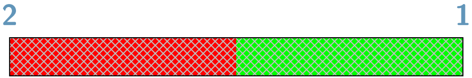

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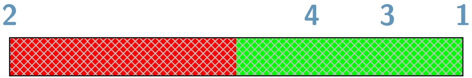

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Gradient Acceptability and Categorical Grammars

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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But mainstream syntactic theories rely on categorical grammars!

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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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The contribution of formal models?

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

- OT-style constraint ranking
- Probabilistic grammars

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- Processing effects
  - Plausibility
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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*?
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Results in pairwise comparisons ideal for the MG parser

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Gradience in Islands: Sprouse et al. (2012)

A factorial design for islands effects:

1. GAP POSITION: Matrix vs. Embedded
2. STRUCTURE: Island vs. Non-Island (Kluender & Kutas 1993)

Jon Sprouse

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A factorial design for islands effects:

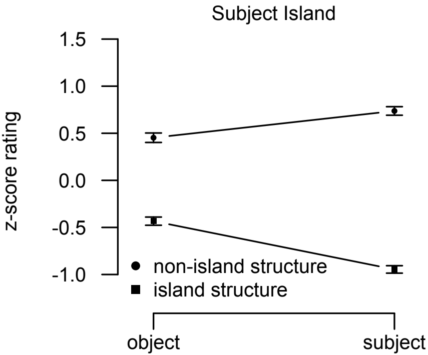
1. Gap Position: Matrix vs. Embedded
2. Structure: Island vs. Non-Island

(Kluender & Kutas 1993)

Jon Sprouse

Results in pairwise comparisons ideal for the MG parser

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

1. Matrix vs. Embedded
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Sprouse at al. (2012)

Four island types

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Gap Position $\times$ Structure

1. Matrix vs. Embedded
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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.	✓

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	Obj. — Non Isl.	>	Subj. — Isl.	✓
	Obj. — Isl.	**>**	**Subj. — Isl.**	×
Subj. Island 2	Matrix — Non Isl.	>	Emb. — Non Isl.	✓
	Matrix — Non Isl.	>	Matrix — Isl.	✓
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	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.	✓
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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

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Obj./Non Island	14/*do*	19
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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?
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Sprouse et al. (2012)			MG Parser
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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.	✓

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 grammar?

- The **first** (quantitative) model of this kind!
- Overall, a success! ⇒ **just** from structural differences!
- Outlier is expected assuming grammaticalized constraints.

The tip of the iceberg!

- Modulate range of dependencies
- Other examples of gradience
- Cognitive vs. grammatical constraints? (Ferrara-Boston 2012)
- Probing industrial-level language models
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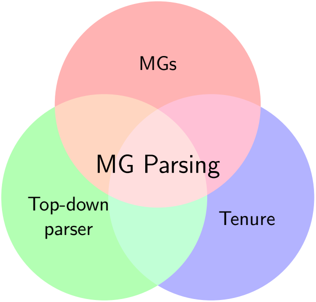
From the Trees (back) to the Forest



- Fully specified parsing model allows for precise predictions
- Tight connection with current generative syntax
- Successful on a variety of cross-linguistic constructions
- + insights about the structure of the grammar

Not Just Theoretical Insights!

- The human parser outperforms our fastest parsers

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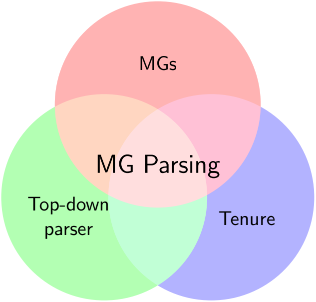

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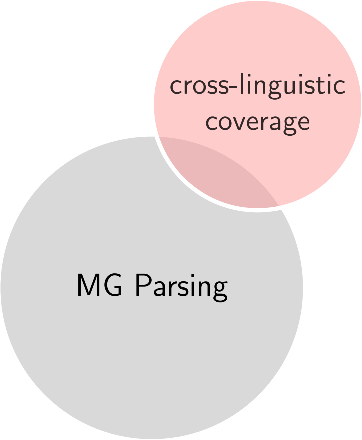

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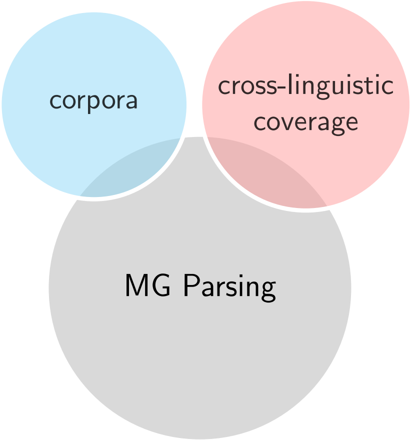

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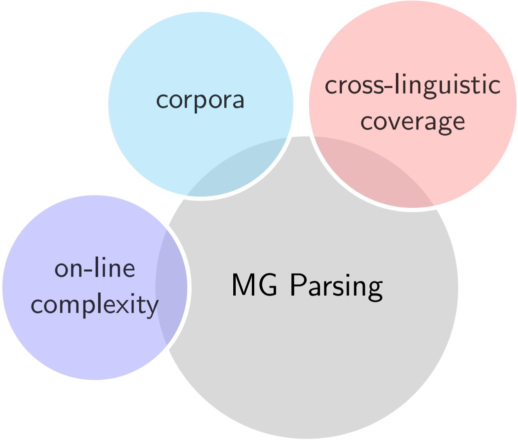

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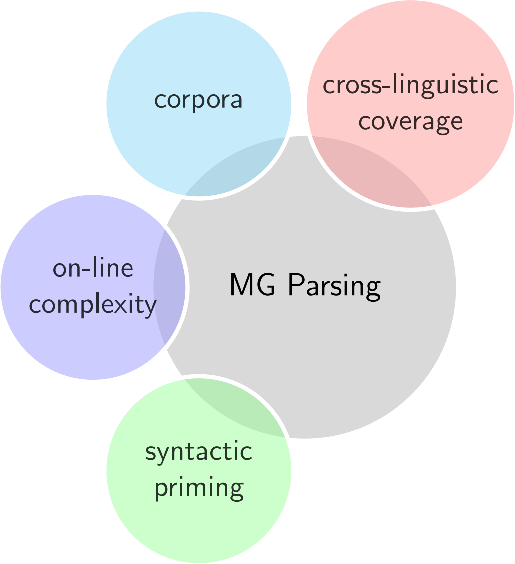

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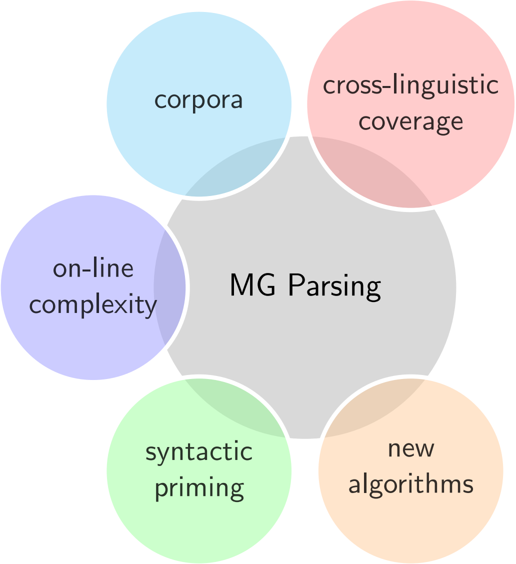

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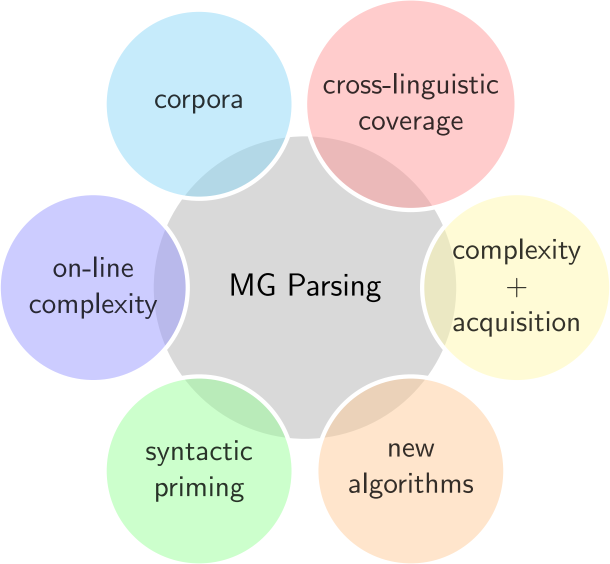

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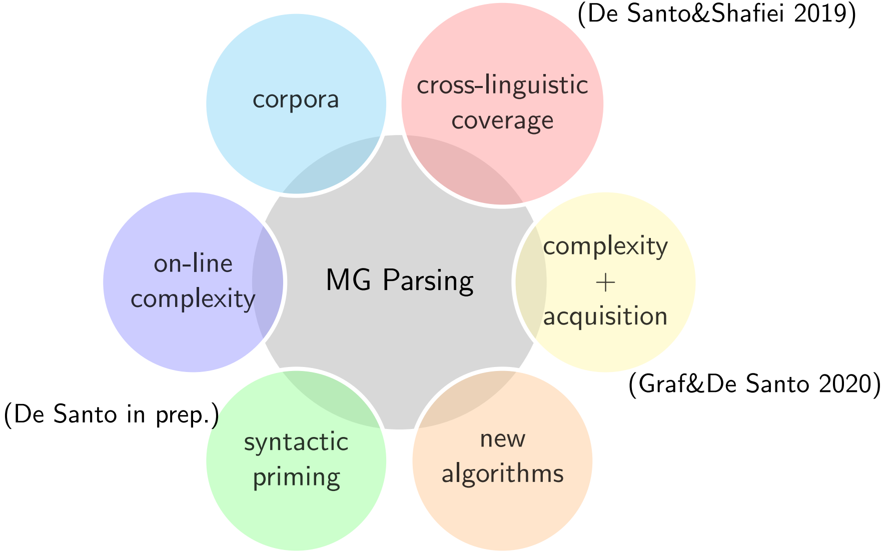

Looking Ahead: A Collaborative Enterprise

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Appendix

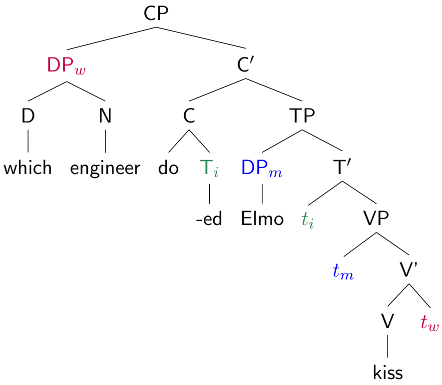
Why MGs?

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)

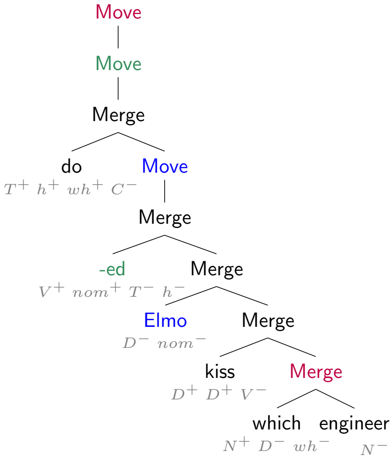
Some Important Properties of MGs

- MGs are weakly equivalent to MCFGs and thus mildly context-sensitive. (Harkema 2001, Michaelis 2001)
- But we can decompose them into two finite-state components: (Michaelis et al. 2001, Kobele et al. 2007, Monnich 2006)
  - a regular language of well-formed derivation trees
  - an MSO-definable mapping from derivations to phrase structure trees
- **Remember:** Every regular tree language can be re-encoded as a CFG (with more fine-grained non-terminal labels). (Thatcher 1967)

Fully Specified Derivation Trees



Phrase Structure Tree



Derivation Tree

Technical Fertility of MGs

MGs can 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)

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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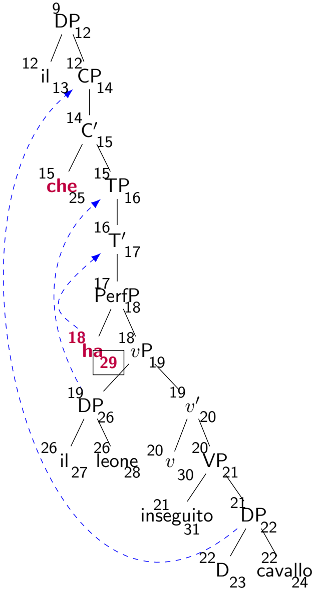
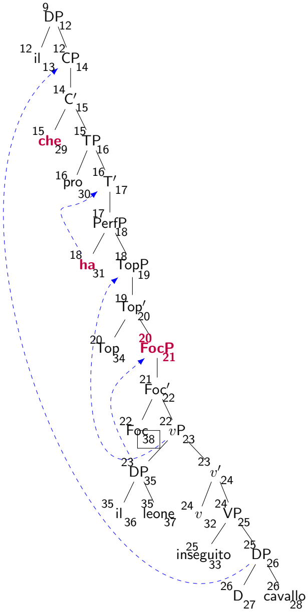
Results: ORC > ORCp





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

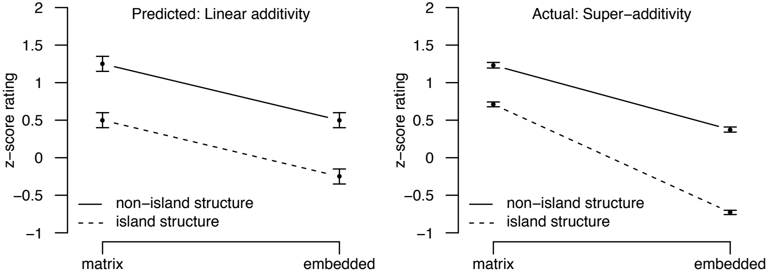
(8) È arrivato Gio
Is arrived Gio
"Gio arrived" **Unaccusative**

(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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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:

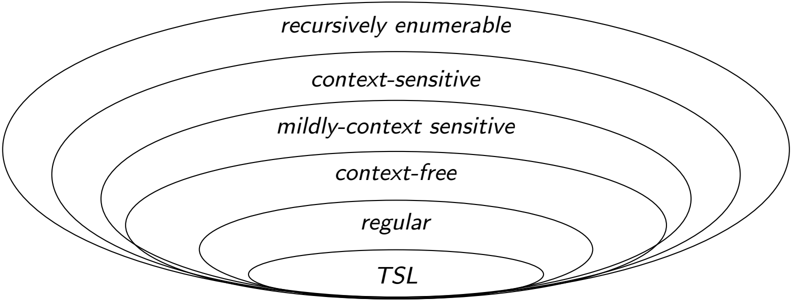
(11) a. Who *t* thinks the speech interrupted the primetime TV show? Matrix — Non Island

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

Subregular Complexity



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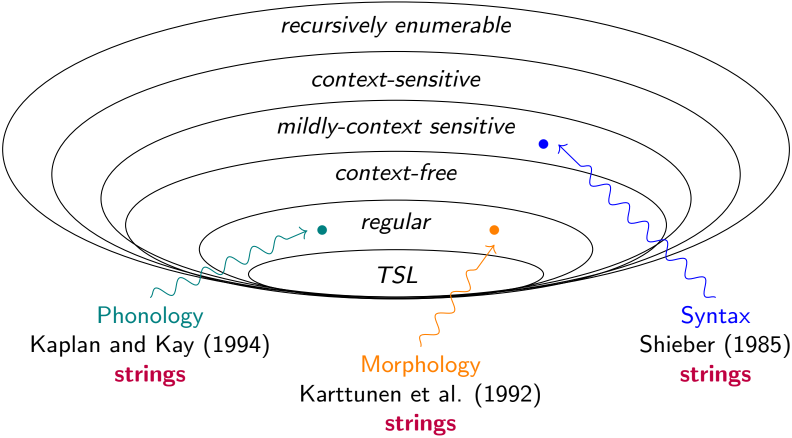

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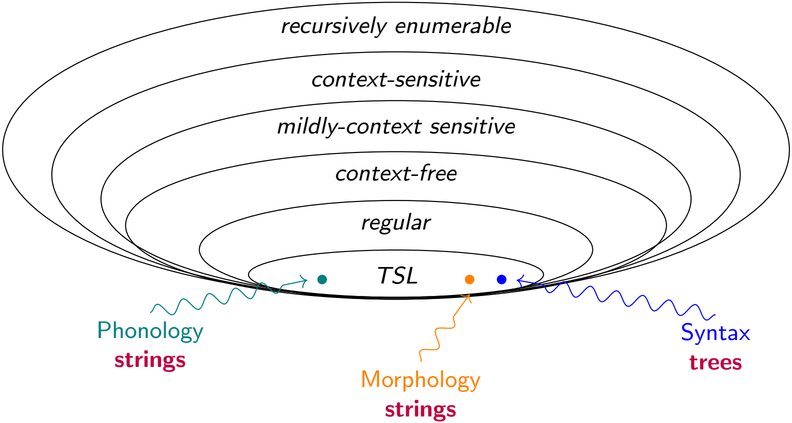

Cognitive Parallelism

Strong Cognitive Parallelism Hypothesis

Phonology, (morphology), and syntax have the **same subregular complexity** over their respective **structural representations**.

We gain a unified perspective on:

- typology
- learnability
- cognition

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