

Extensible Dependency Grammar: A Modular Grammar Formalism Based On Multigraph Description

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What the thesis is about

- Extensible Dependency Grammar (XDG)
- new grammar formalism for natural language
- explores the combination of:
 - 1 dependency grammar
 - 2 model theory
 - 3 parallel architecture
- results:
 - 1 modularity: grammars can be extended by any linguistic aspect, each modeled independently
 - 2 emergence: complex linguistic phenomena emerge as the intersection of the linguistic aspects

Overview

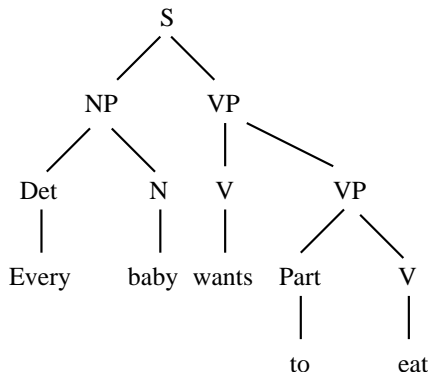
- 1 Introduction
- 2 Formalization
- 3 Implementation
- 4 Application
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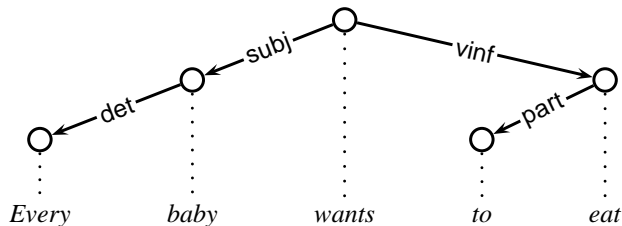
Dependency Grammar

- traditional (Chomsky 1957): syntax of natural language analyzed in terms of phrase structure grammar:
 - hierarchically arranges substrings called phrases
 - nodes labeled by syntactic categories



Dependency Grammar

- dependency grammar (Tesnière 1959):
 - hierarchically arranges words
 - edges labeled by grammatical functions
 - mothers: heads, daughters: dependents

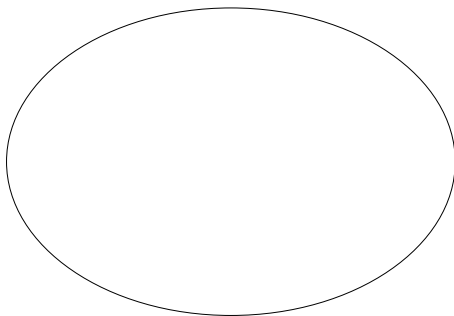


Advantages

- flexibility: dependency analyses need not be trees but can be arbitrary graphs
- need not be ordered
- perfectly suited for modeling linguistic aspects other than syntax, e.g. predicate-argument structure, where the models are unordered DAGs

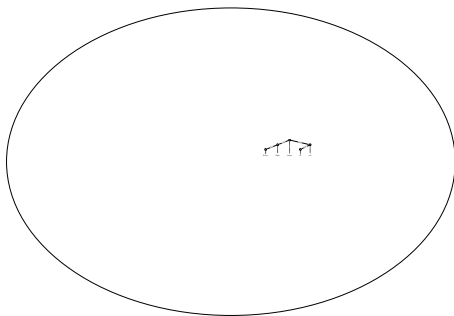
Model Theory

- traditional: generative perspective on grammar (Chomsky 1957):
 - 1 start with the empty set
 - 2 use production rules to generate the well-formed models



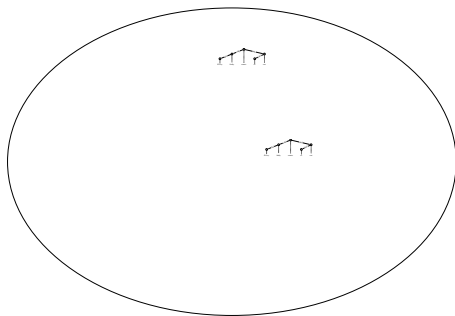
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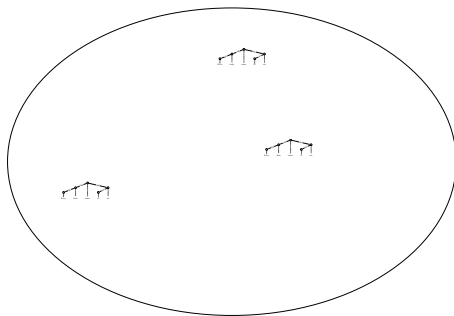
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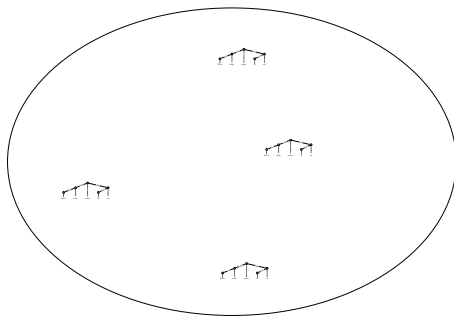
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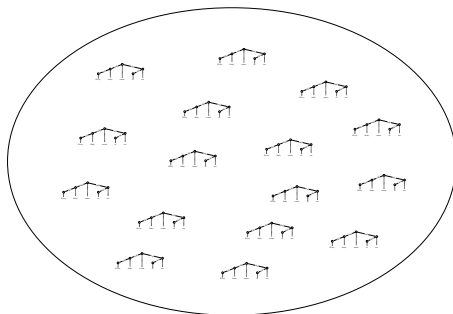
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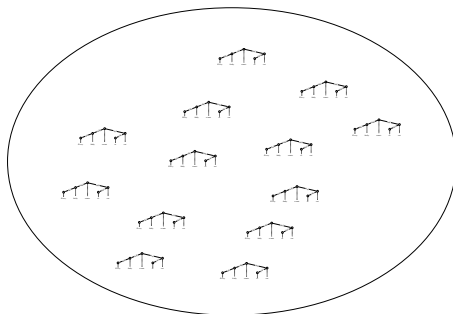
Model Theory

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 - 1 start with the set of all possible models
 - 2 use well-formedness conditions to eliminate all non-well-formed models



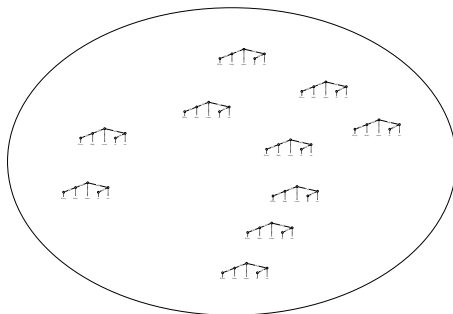
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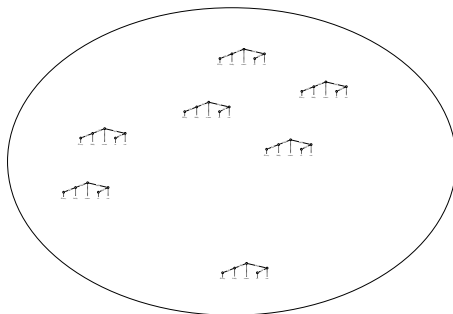
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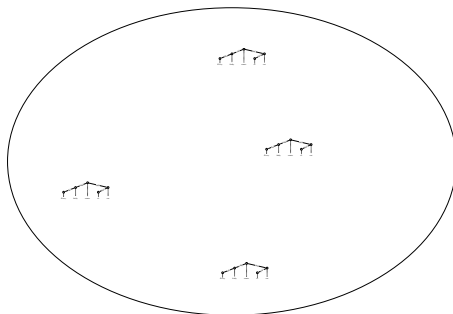
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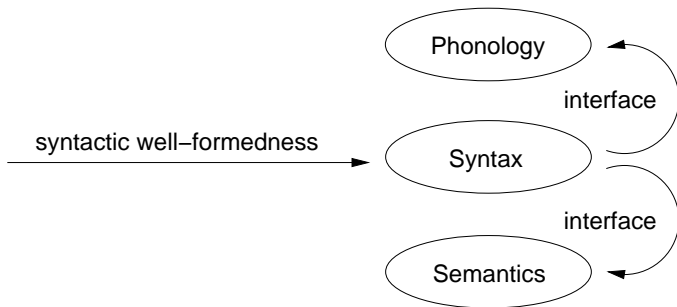


Advantage

- declarativity: constraints describe the well-formed models independently of any underlying mechanisms

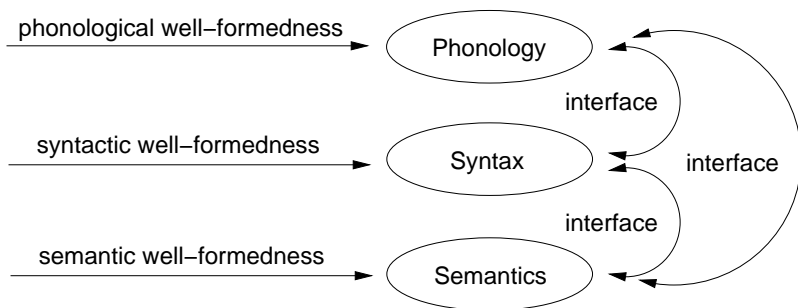
Parallel Architecture

- traditional: syntacto-centric architecture (Chomsky 1965):
 - only syntax modeled independently
 - other linguistic aspects obtained by functional interfaces



Parallel Architecture

- parallel architecture (Jackendoff 2002), (Sadock 1991):
 - all linguistic aspects modeled independently
 - relational interfaces



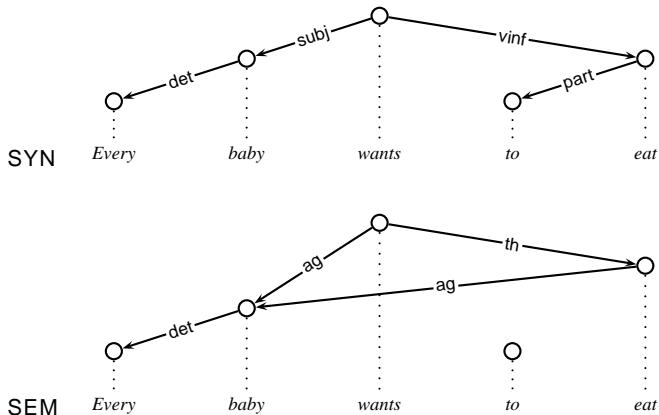
Advantages

- modularity: linguistic aspects can be modeled largely independently of each other
- emergence: complex phenomena emerge as the intersection of the linguistic aspects

Extensible Dependency Grammar (XDG)

- combines:
 - 1 flexibility from dependency grammar
 - 2 declarativity from model theory
 - 3 modularity and emergence from the parallel architecture
- models: dependency multigraphs, i.e. tuples of dependency graphs
- share the same set of nodes
- arbitrary many components called dimensions

Example Multigraph



Related Work

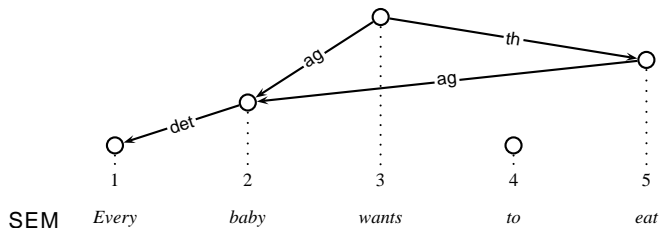
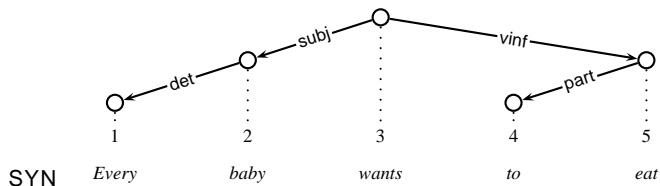
- phrase structure grammar:
 - Generative Grammar (Chomsky 1957, 1965, 1981, 1995)
 - Tree Adjoining Grammar (Joshi 1987)
 - Combinatory Categorical Grammar (Steedman 2000)
 - Head-driven Phrase Structure Grammar (Pollard/Sag 1994)
 - Lexical-Functional Grammar (Bresnan 2001)
- dependency grammar:
 - Functional Generative Description (Sgall et al. 1986)
 - Meaning Text Theory (Mel'čuk 1988)
 - Constraint Dependency Grammar (Menzel/Schröder 1998)
 - Topological Dependency Grammar (Duchier/Debusmann 2001)

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Dependency Multigraphs

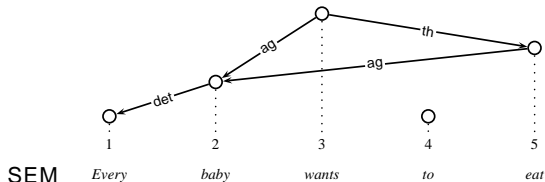
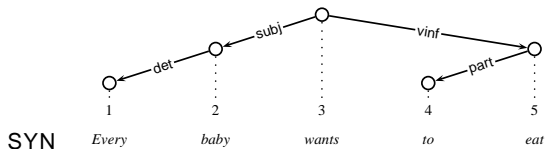
- tuples (V, D, W, w, L, E, A, a)



Relations

- 3 relations:

- 1 labeled edge
- 2 strict dominance
- 3 precedence



Grammar

- $G = (MT, P)$, characterizes set of multigraphs:
 - ① MT : multigraph type determining dimensions, words, edge labels
 - ② P : set of principles constraining the set of well-formed multigraphs of type MT
- principles P formulated in a higher order logic
- signature determined by MT

Models and String Language

- the models of $G = (MT, P)$ are all multigraphs which:
 - ① have multigraph type MT
 - ② satisfy all principles P
- the string language of a grammar G are all strings s such that:
 - ① there is a model of G with as many nodes as words in s
 - ② concatenation of the words of the nodes yields s

Principles

- formulas in higher order logic
- characterize the well-formed multigraphs of a specific multigraph type
- predefined principle library from which grammars can be built like with lego bricks (Debusmann et al. 2005 FGMOL), e.g.:
 - tree principle
 - valency principle
 - order principle

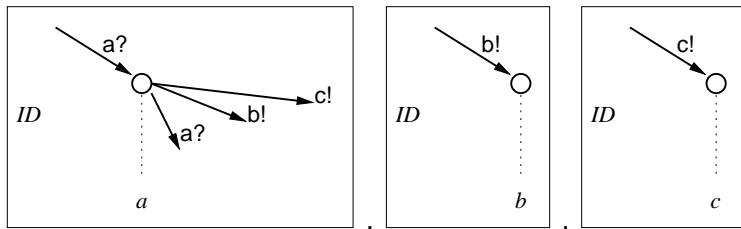
Tree Principle

- given a dimension d , there must be:
 - 1 no cycles
 - 2 precisely one node without an incoming edge (the root)
 - 3 each node must have at most one incoming edge

$$\begin{aligned} \forall v : \neg(v \rightarrow_d^+ v) & \quad \wedge \\ \exists^1 v : \neg \exists v' : v' \rightarrow_d v & \quad \wedge \\ \forall v : \neg \exists v' : v' \rightarrow_d v \vee \exists^1 v' : v' \rightarrow_d v \end{aligned}$$

Valency Principle

- lexically constrains the incoming and outgoing edges of the nodes
- characterized by fragments, e.g.:

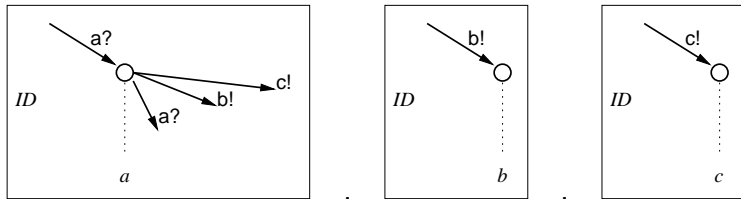


Grammar 1

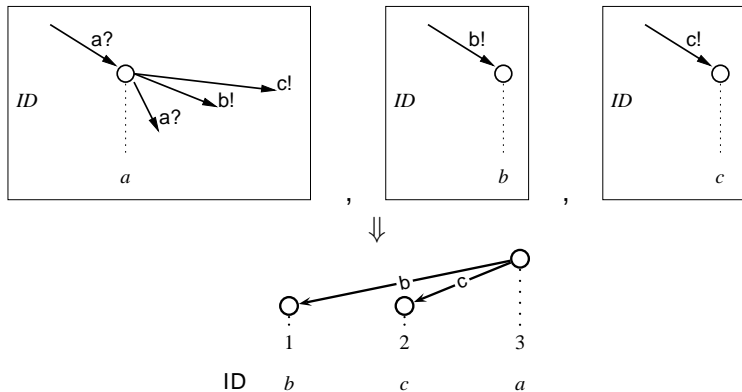
- together with the tree principle, the fragments yield our first grammar
- string language: equally many *as*, *bs* and *cs* in any order:

$$L_1 = \{w \in (a \cup b \cup c)^+ \mid |w|_a = |w|_b = |w|_c\}$$

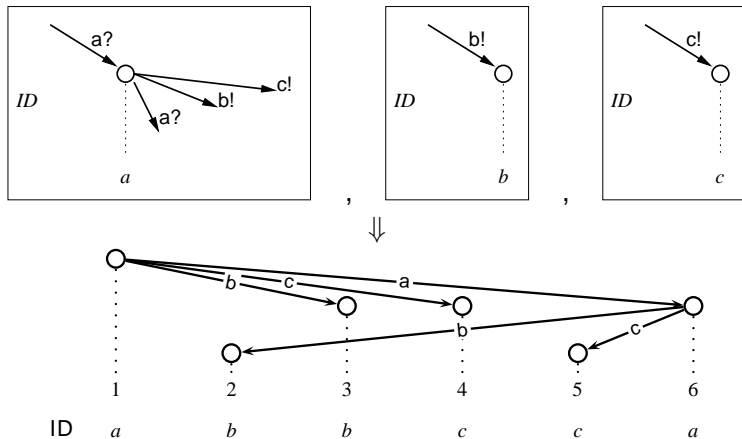
- why? *as* arranged in a chain, each *a* has precisely one outgoing edge to *b* and one to *c*:



Example Analyses

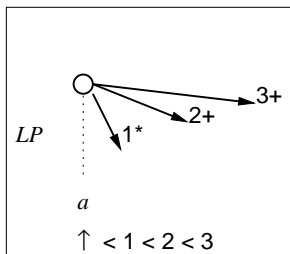


Example Analyses



Order Principle

- lexically constrains:
 - the order of the outgoing edges of the nodes depending on their edge labels
 - the order of the mother with respect to the outgoing edges, also depending on their edge labels
- characterized by ordered fragments, e.g.:

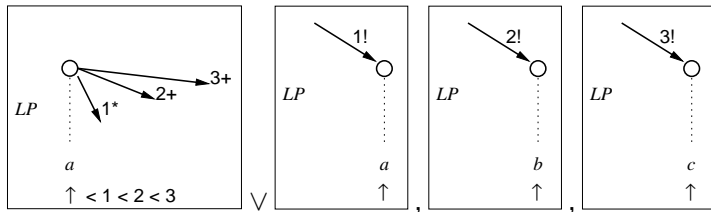


Grammar 2

- string language: one or more a followed by one or more bs followed by one or more cs :

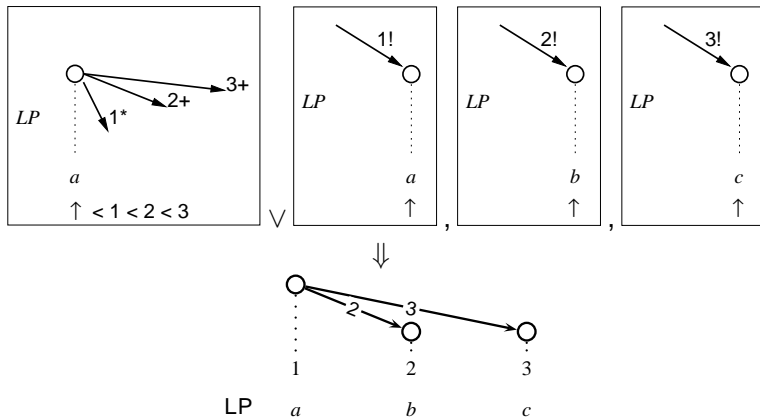
$$L_2 = \{w \in a^+b^+c^+\}$$

- tree, valency and order principles and the fragments below:

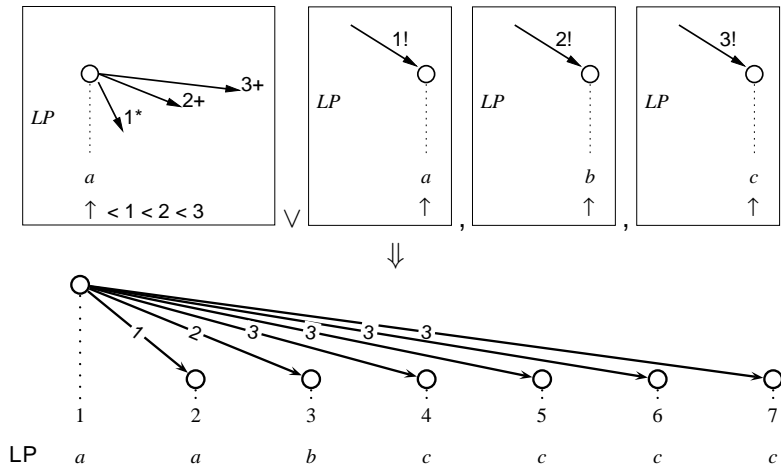


- idea: a is always root, licensing zero or more outgoing edges labeled 1 to as , and one or more labeled 2 to bs and 3 to cs , where the as precede the bs precede the cs :

Example Analyses



Example Analyses



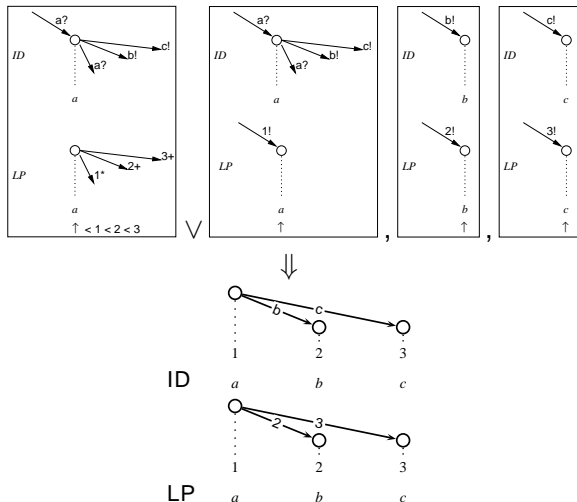
Intersection of Dimensions

- intersection of the two languages L_1 and L_2 yields the string language of n *as* followed by n *bs* followed by n *cs*:

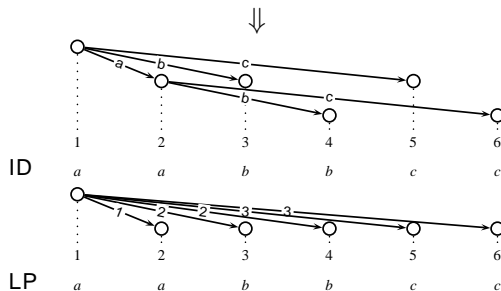
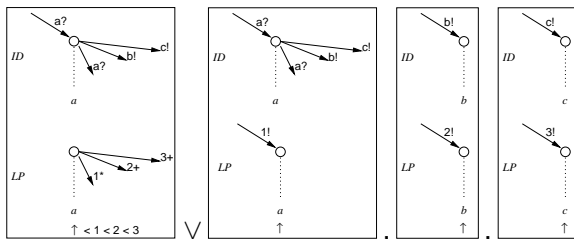
$$L_1 \cap L_2 = \{w \in a^n b^n c^n \mid n \geq 1\}$$

- modeled by intersecting dimensions:
 - 1 ID dimension of grammar 1 ensures that there are equally many *as*, *bs* and *cs*
 - 2 LP dimension of grammar 2 orders the *as* before the *bs* before the *cs*

Example Analyses



Example Analyses



Scrambling

- German subordinate clauses: nouns followed by the verbs:

(dass) ein Mann Cecilia die Nilpferde füttern sah
(that) a man Cecilia the hippos feed saw
“(that) a man saw Cecilia feed the hippos”

- all permutations of the nouns grammatical, i.e., also:

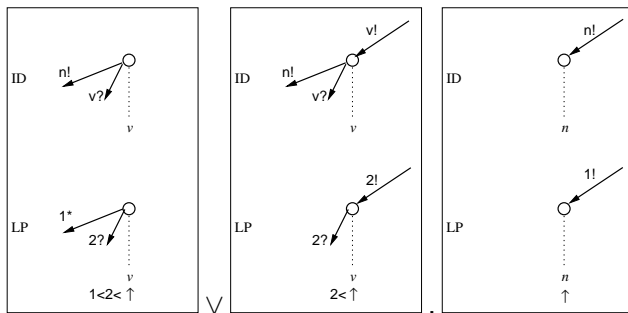
(dass) ein Mann die Nilpferde Cecilia füttern sah
(dass) die Nilpferde ein Mann Cecilia füttern sah
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Idealization

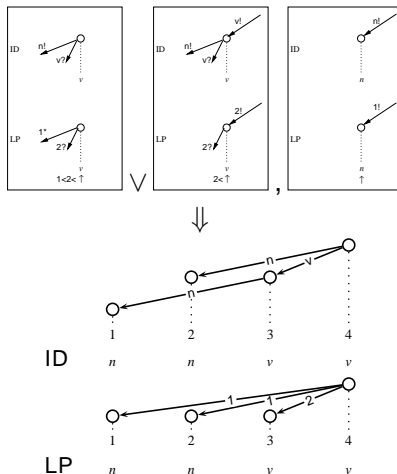
- idealized language:

$$\text{SCR} = \{ \sigma(n^{[1]}, \dots, n^{[k]}) v^{[k]} \dots v^{[1]} \mid k \geq 1 \text{ and } \sigma \text{ a permutation} \}$$

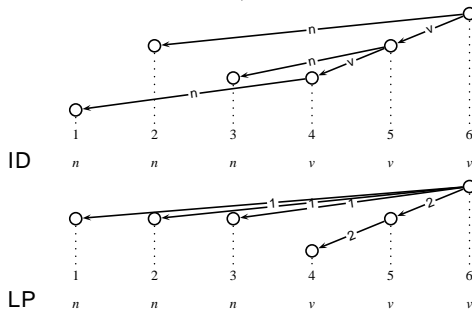
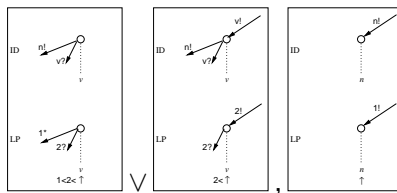
- grammar: ID dimension pairs verbs and nouns, LP dimension orders nouns before verbs



Example Analyses



Example Analyses



Expressivity

- can model lexicalized context-free grammar (constructive proof in thesis)
- can go far beyond context-free grammar:
 - $a^n b^n c^n$ already non-context free
 - can model TAG (Debusmann et al. 2004 TAG+7): mildly context-sensitive
 - cross-serial dependencies (thesis): also mildly context-sensitive
 - scrambling: beyond the mildly context-sensitive Linear Context-Free Rewriting Systems (LCFRS) (Becker et al. 1992)
- put to use in an elegant account of German word order phenomena in (Duchier/Debusmann 2001), (Debusmann 2001), (Bader et al. 2004)

Complexity

- recognition problem: NP-hard (reduction to SAT in thesis) (Debusmann/Smolka 2006)
- restrictions on principles:
 - first-order: upper bound in PSPACE
 - polynomially testable: upper bound in NP
- all principles written so far first-order
- all principles implemented as polynomially testable constraints in Mozart/Oz
- i.e., practical upper bound: in NP

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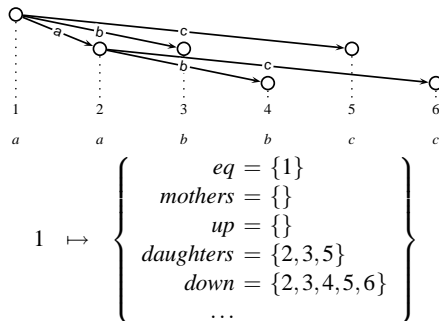
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Implementation

- how to process an NP-hard problem?
- constraint programming (Schulte 2002), (Apt 2003): solving of constraint satisfaction problems (CSPs)
- CSPs stated in terms of:
 - 1 constraint variables, here on finite sets of integers
 - 2 constraints on them
- solutions of a CSP determined by two interleaving processes:
 - 1 propagation: application of deterministic inference rules
 - 2 distribution: non-deterministic choice
- XDG parsing regarded as a CSP in Mozart/Oz (Smolka 1995), based on techniques developed in (Duchier 1999, 2003)

Modeling Dependency Multigraphs

- dependency graphs: nodes identified with integers, each node associated with a set of finite set of integers variables, e.g.:



- dependency multigraphs: variables duplicated for each dimension

Modeling Principles

- principles can now be transformed into constraints on finite sets of integers
- e.g. the tree principle:

```
for Node in Nodes do
  %% no cycles
  {FS.disjoint Node.eq Node.down}

  %% one root
  {FS.card Roots}=:1

  %% at most one incoming edge
  {FS.card Node.mothers}<=:1
end
```

Features

- concurrent: all dimensions processed in parallel
- reversible: can be used for parsing and generation (Koller/Striegnitz 2002), (Debusmann 2004)
- supports underspecification: e.g. of quantifier scope, PP attachment (Debusmann et al. 2004 COLING)
- efficient for handcrafted grammars
- first successful experiments in large-scale parsing with the XTAG grammar (> 100.000 lexical entries) after thesis submission

Grammar Development Kit

- extensive grammar development kit built around the constraint parser (35000 code lines): XDG Development Kit (XDK) (Debusmann et al. 2004 MOZ)
- example grammars (24000 additional lines):
 - German grammar developed in (Debusmann 2001)
 - Arabic grammar developed in (Odeh 2004)
 - toy grammars for Czech, Dutch and French
 - implementations of all example grammars in the thesis
- graphical user interface
- complete documentation (200+ pages)
- application:
 - successfully used for teaching (ESSLLI 2004, FoPra)
 - module in an engine for interactive fiction (Koller et al. 2004)

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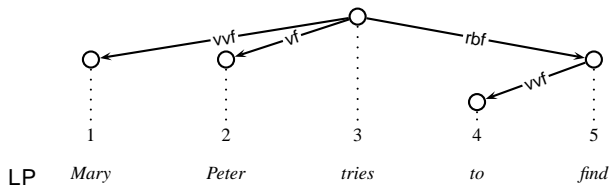
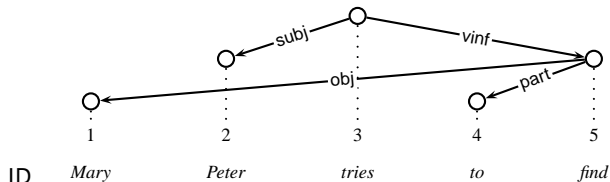
Application to Natural Language

- English example grammar developed in the thesis models fragments of:
 - syntax
 - semantics
 - phonology
 - information structure
- interfaces:
 - relational syntax-semantics interface (Korthals/Debusmann 2002), (Debusmann et al. 2004 COLING)
 - relational phonology-information structure interface (Debusmann et al. 2005 CICLING)

Syntax

- based on topological analysis of German (Duchier/Debusmann 2001)
- ID dimension: models grammatical functions
- LP dimension: models word order using topological fields
- intersection of ID/LP leads to the emergence of complex English word order phenomena:
 - topicalization
 - wh-questions
 - pied piping

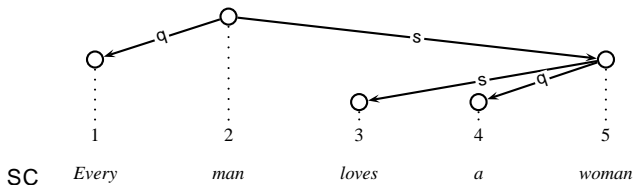
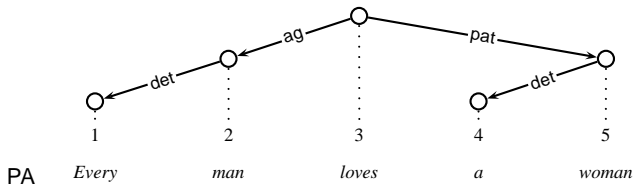
Topicalization



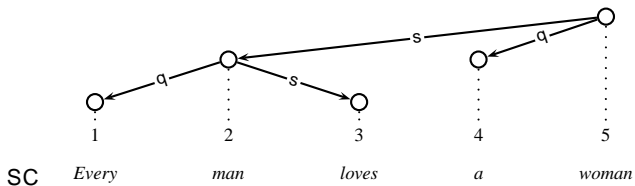
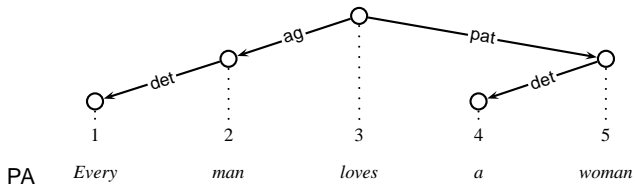
Semantics

- PA dimension: models predicate-argument structure
- SC dimension: models quantifier scope
- supports scope underspecification
- interface to the Constraint Language for Lambda Structures (CLLS) (Egg et al. 2001)

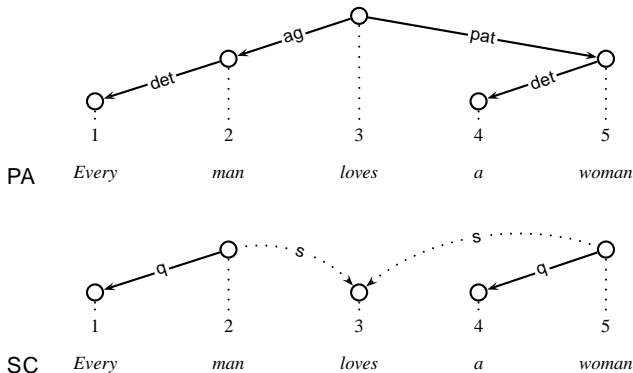
Example (Weak Reading)



Example (Strong Reading)



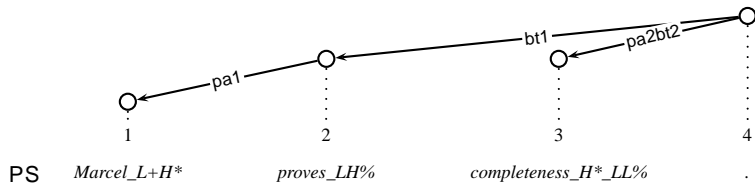
Example (Underspecification)



Phonology

- PS dimension: models prosody
- sentence divided into prosodic constituents marked by boundary tones
- prosodic constituents headed by pitch accents

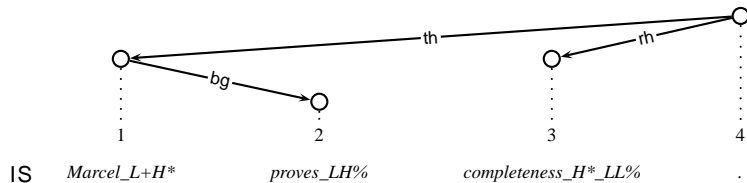
Example



Information Structure

- IS dimension
- sentence divided into information structural constituents using the theme/rheme dichotomy
- information structural constituents: divided into focus and background

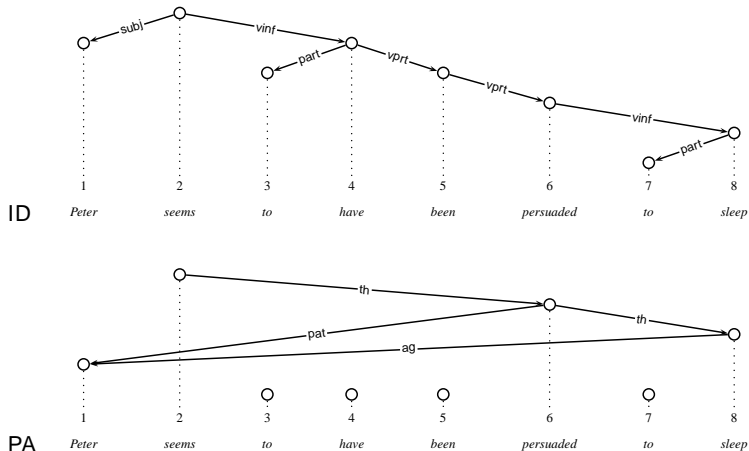
Example



Syntax-Semantics Interface

- relational interface between ID and PA dimensions
- modular modeling: independent of word order (LP) and quantifier scope (SC)
- intersection of ID/PA leads to the emergence of:
 - control/raising
 - auxiliary constructions (e.g. passives)
- supports underspecification of PP-attachment

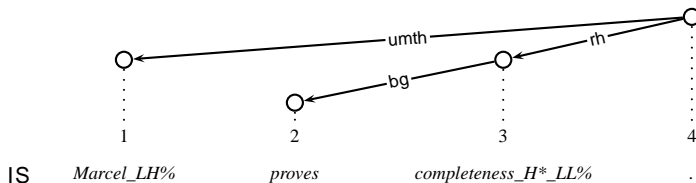
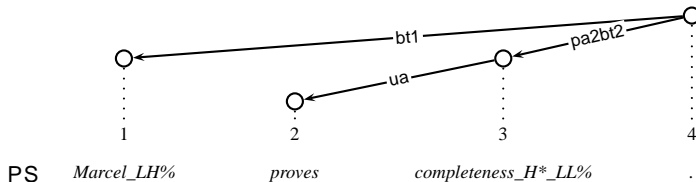
Control/Raising and Passive Example



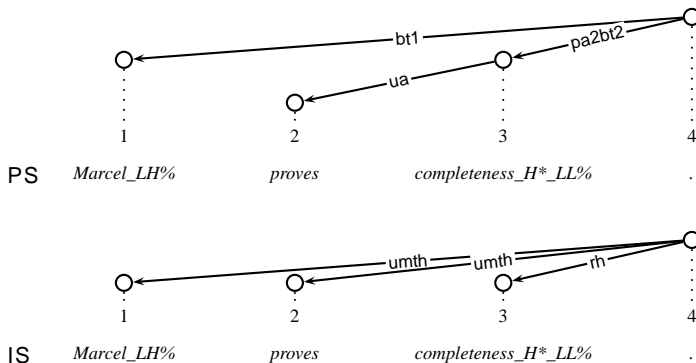
Phonology-Semantics Interface

- relational interface between PS and IS dimensions
- modular modeling: independent of any other linguistic aspect
- based on the prosodic account of information structure developed in (Steedman 2000)
- intersection of PS and IS dimensions leads e.g. to the emergence of the unmarked theme ambiguity phenomenon

Unmarked Theme Example



Unmarked Theme Example



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Summary

- with XDG, explored combination of dependency grammar, model theory and parallel architecture
- formalization:
 - higher order logic
 - expressivity: far beyond context-free grammar
 - practical complexity: NP-complete
- implementation:
 - parser based on constraint programming in Mozart/Oz
 - comprehensive grammar development kit (XDK)
- application:
 - example grammar modeling fragments of natural language syntax, semantics, phonology and information structure
- main results:
 - 1 new degree of modularity
 - 2 phenomena emerge by the intersection of individual dimensions, without further stipulation

Selected Publications I



Ralph Debusmann, Denys Duchier, Alexander Koller, Marco Kuhlmann, Gert Smolka, and Stefan Thater.

A relational syntax-semantics interface based on dependency grammar.

In Proceedings of COLING 2004, Geneva/CH, 2004.



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Future Work

- formalization:
 - strengthen relation to other grammar formalisms, e.g. FGD, TAG
 - formalize XDG in a weaker logic, e.g. MSO
- implementation:
 - make use of new constraint technology, e.g. Gecode (Schulte/Tack 2005), (Schulte et al. 2006)
 - automatically generate principle implementations

Thank you!

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