Multi-dimensional Dependency Grammar as Graph Description

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Overview

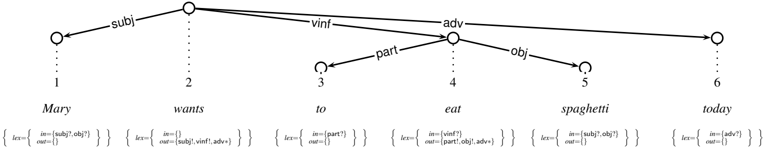
Overview

Two Trends in Natural Language Processing

- dependency grammar (Tesniere 1959), (Mel'čuk 1988)
- multi-layered linguistic description

Dependency Grammar

- collection of ideas for the analysis of natural language
- example analysis of *Mary wants to eat spaghetti today*:



- graph, 1:1-mapping nodes:words, dependency relations, valency
- e.g.: *wants*:

$$\left\{ \; lex = \left\{ \begin{array}{rcl} in & = & \{\} \\ out & = & \{\mathsf{subj!}, \mathsf{vinf!}, \mathsf{adv}*\} \end{array} \right\} \; \right\}$$

Dependency Grammar as a trend

- incorporated into grammar formalisms: CCG (Steedman 2000), HPSG (Pollard/Sag 1994), LFG (Bresnan/Kaplan 1982), TAG (Joshi 1987)
- indispensable for statistical parsing (Collins 1999)
- treebanks: Prague Dependency Treebank (Bohmova et al. 2001), Danish Dependency Bank, TiGer Dependency Bank (Forst et al. 2004)

Multi-layered Linguistic Description

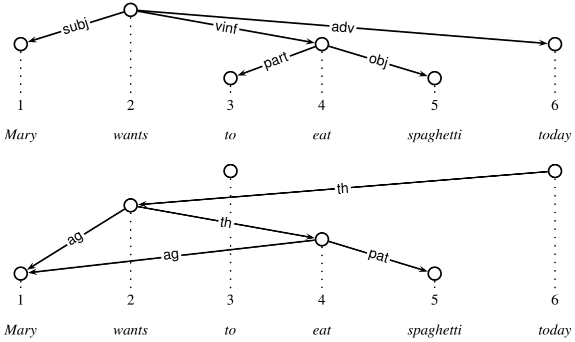
- additional layers of annotation
- predicate-argument structure: PropBank (Kingsbury/Palmer 2002), SALSA (Erk et al. 2003), tectogrammatical structure of the PDT
- information structure: PDT
- discourse structure: Penn Discourse Treebank (Webber et al. 2005)
- annotation: mostly dependency-based
- can we represent these layers as modules in one framework based on dependency grammar?

Extensible Dependency Grammar (XDG)

- new grammar formalism (Debusmann 2006 PhD)
- supports arbitrary many layers of linguistic description called "dimensions", all sharing the same set of nodes
- model-theoretic: models called "multigraphs"

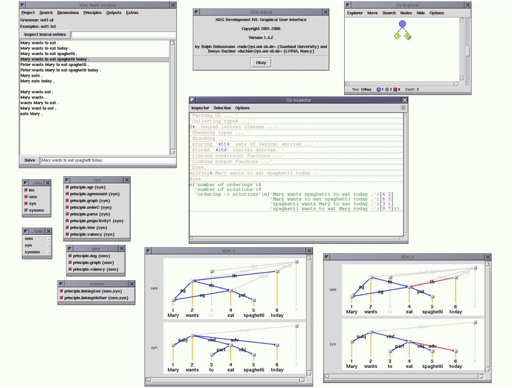
Multigraph

- syntax and predicate-argument structure:



Implementation

- concurrent constraint-based parser written in Mozart/Oz (Mozart06)
- XDG Development Kit (XDK) (Debusmann et al. 2004 MOZ)



Application

- German syntax (Duchier/Debusmann 2001 ACL), (Debusmann 2001), (Bader et al. 2004)
- Arabic syntax (Odeh 2004)
- English syntax (Debusmann 2006 PhD)
- relational syntax-semantics interface (Debusmann et al. 2004 COLING)
- prosodic account of information structure (Debusmann et al 2005 CICLING)

Two Stumbling Blocks

1. no complete formalization (Debusmann et al. 2005 FG-MOL)
2. no efficient large-scale parsing (Bojar 2004), (Moehl 2004), (Narendranath 2004)

Overview

A Description Language for Multigraphs

- formalization as a description language for multigraphs in higher order logic
- expressed in simply typed lambda calculus extended with finite domains and records
- types, given set of atoms At:

$$
\begin{array}{llll}
a \in At & & & \\
T \in Ty & ::= & \mathsf{B} & \text{boolean} \\
 & \mid & \mathsf{V} & \text{node} \\
 & \mid & T_1 \to T_2 & \text{function} \\
 & \mid & \{a_1, \ldots, a_n\} & \text{finite domain } (n \geq 1) \\
 & \mid & \{a_1 : T_1, \ldots, a_n : T_n\} & \text{record}
\end{array}
$$

- interpretation: $\mathsf{B} = \{0, 1\}$, $\mathsf{V} = \{1, 2, \ldots, n\}$ given n nodes, i.e., both base types finite

Multigraph Type

- signature of XDG varies according to the dimensions, words, edge labels and attributes of the described multigraphs
- multigraph type: $MT = (Dim, Word, lab, attr)$
- domains of dimensions and words must be finite

Signature

- multigraph constants, given multigraph type $MT = (Dim, Word, lab, attr)$:

$$
\begin{array}{rcll}
\stackrel{\cdot}{\longrightarrow}_d & : & \mathsf{V} \rightarrow \mathsf{V} \rightarrow lab\ d \rightarrow \mathsf{B} & \text{labeled edge } (d \in Dim) \\
< & : & \mathsf{V} \rightarrow \mathsf{V} \rightarrow \mathsf{B} & \text{precedence} \\
(W\ \cdot) & : & \mathsf{V} \rightarrow Word & \text{node-word mapping} \\
(d\ \cdot) & : & \mathsf{V} \rightarrow attr\ d & \text{node-attributes mapping } (d \in Dim)
\end{array}
$$

- logical constant:

$$
\doteq_T \quad : \quad T \rightarrow T \rightarrow \mathsf{B} \quad \text{equality (for each type } T\text{)}
$$

Grammar, models and string language

- grammar: $G = (MT, P)$
- P set of formulas called “principles”, i.e., the well-formedness conditions
- models: all multigraphs with multigraph type MT and which satisfy P
- string language: set of all strings $s = w_1 \dots w_n$ such that:
  1. there are as many nodes as words: $V = \{1, \dots, n\}$
  2. concatenating the words of the nodes yields s: $(W\ 1) \dots (W\ n) = s$

Tree Principle

- three conditions:
  1. There are no cycles.
  2. There is precisely one root.
  3. Each node has at most one incoming edge.
- principle definition:

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

Other Principles

- DAG
- valency
- order
- projectivity
- agreement
- linking
- etc. (Debusmann 2006 PhD)

Overview

Recognition Problems

- universal recognition problem: given a pair (G, s) where G is a grammar and s a string, is s in $L(G)$?
- fixed recognition problem: let G be a fixed grammar. Given a string s, is s in $L(G)$?
- plan: prove NP-hardness of the fixed recognition problem, NP-hardness of the universal then falls out

Reduction

- proof by reducing the NP-complete SAT problem to the fixed XDG recognition problem
- SAT: does a propositional formula f have an assignment that evaluates to true?
- propositional formula:

$$\begin{array}{rll} f ::= & X, Y, Z, \ldots & \text{variable} \\ \mid & 0 & \text{false} \\ \mid & f_1 \Rightarrow f_2 & \text{implication} \end{array}$$

Input Preparation

- 2 challenges:
  1. propositional formulas can be ambiguous
  2. can contain arbitrary many variables, but an XDG grammar only has a finite set of words
- input preparation function: $prep : f \longrightarrow Word$
- example formula: $(X \Rightarrow Y) \Rightarrow Y$
  1. prefix notation:

$$\Rightarrow \Rightarrow X\ Y\ Y$$

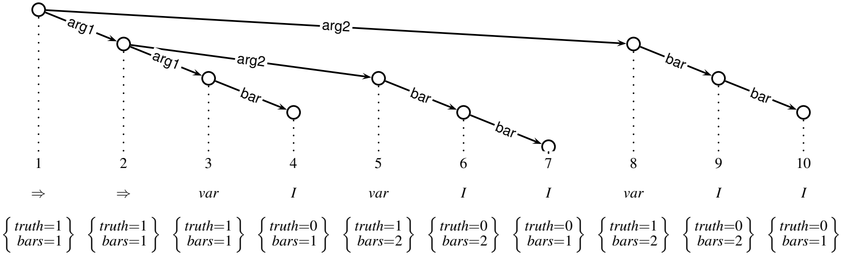
  2. unary encoding:

$\Rightarrow \Rightarrow$ *var I var I I var I I*

Models

- representation of the example formula $(X \Rightarrow Y) \Rightarrow Y$:

$\Rightarrow \Rightarrow$ *var I var I I var I I*



Coreference

- which type for the “bars” attribute?
- idea: use V, whose interpretation is a finite interval of the natural numbers starting with 1, because:
  1. there are always more nodes in the analysis than variables in the formula, i.e., V always includes enough elements to distinguish all variables
  2. bars can be counted by emulating incrementation with the precedence predicate:

$$incr \quad = \quad \lambda v, v'. \quad v < v' \; \wedge \; \neg \exists v'' : v < v'' \; \wedge \; v'' < v'$$

NP-hardness of the Fixed Recognition Problem

- Given a formula f and the fixed XDG grammar G defined above, f is satisfiable if and only if $prep\ f \in L(G)$, i.e., SAT is reducible to the fixed recognition problem for XDG.
- as the reduction is polynomial, the fixed recognition problem for XDG is NP-hard
- universal recognition problem: generalization of the fixed recognition problem, thus also NP-hard

Upper Bounds

- principles first order: upper bound in PSPACE
- principles testable in polynomial time: upper bound in NP (all principles defined so far)

Overview

Summary

- XDG is a showcase for two trends in NLP: dependency grammar and multi-layered linguistic description
- but: two stumbling blocks: no complete formalization, no efficient large-scale parsing
- this talk: first complete formalization of XDG as a description language for multigraphs
- complexity: NP-hard, upper bound: with realistic restrictions: in NP

Future Work

- XDG parser: constraint-based parser, complete, concurrent, efficient for handcrafted grammars
- but does not yet scale up to large-scale parsing
- future work:
  1. optimizing the constraint-based parser: find global constraints, Gecode (Schulte/Stuckey 2004), (Schulte/Tack 2005), statistical support (supertagging)
  2. finding polynomially parsable fragments of XDG, e.g. related to TAG, STAG or GMTG (Melamed et al. 2004)

Thanks for your attention!

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Notational Conveniences

- strict dominance:

$$v \rightarrow_d^+ v' \stackrel{\text{def}}{=} v \rightarrow_d v' \vee (\exists v'' : v \rightarrow_d v'' \wedge v \rightarrow_d^+ v'')$$

Principles: Roots, Implications and Zeros

- roots:

$$\begin{array}{l} plRoots = \forall v : \\ \quad \neg\exists v' : v' \rightarrow_{\mathsf{PL}} v \ \Rightarrow \ (\mathsf{PL}\ v).truth \doteq 1 \end{array}$$

- implications:

$$\begin{array}{l} plImpls = \forall v, v', v'' : \\ \quad (v \xrightarrow{\mathsf{arg1}}_{\mathsf{PL}} v' \ \wedge \ v \xrightarrow{\mathsf{arg2}}_{\mathsf{PL}} v'' \ \Rightarrow \\ \quad (\mathsf{PL}\ v).truth \doteq ((\mathsf{PL}\ v').truth \ \Rightarrow \ (\mathsf{PL}\ v'').truth)) \wedge \\ \quad (\mathsf{PL}\ v).bars \doteq 1 \end{array}$$

- zeros:

$$\begin{array}{l} plZeros = \forall v : \\ \quad (W\ v) \doteq 0 \ \Rightarrow \\ \quad (\mathsf{PL}\ v).truth \doteq 0 \wedge \\ \quad (\mathsf{PL}\ v).bars \doteq 1 \end{array}$$

Principles: Variables and Bars

- variables:

$$
\begin{array}{l}
plVars = \forall v, v' : \\
\quad (W\ v) \doteq \textit{var} \Rightarrow \\
\quad v \xrightarrow{\mathsf{bar}}_{\mathsf{PL}} v' \ \Rightarrow \ (\mathsf{PL}\ v).bars \doteq (\mathsf{PL}\ v').bars
\end{array}
$$

- bars:

$$
\begin{array}{l}
plBars = \forall v : \\
\quad (W\ v) \doteq I \ \Rightarrow \\
\quad (\mathsf{PL}\ v).truth \doteq 0 \wedge \\
\quad \neg\exists v' : v \rightarrow_{\mathsf{PL}} v' \Rightarrow (\mathsf{PL}\ v).bars \doteq 1 \wedge \\
\quad (\forall v' : v \xrightarrow{\mathsf{bar}}_{\mathsf{PL}} v' \Rightarrow incr\ v'\ v)
\end{array}
$$

Principles: Coreference

- coreference:

$$
\begin{array}{l}
plCoref = \forall v, v' : \\
\quad (W\ v) \doteq \textit{\textsf{var}} \wedge (W\ v') \doteq \textit{\textsf{var}} \Rightarrow \\
\quad (\textsf{PL}\ v).bars \doteq (\textsf{PL}\ v').bars \Rightarrow (\textsf{PL}\ v).truth \doteq (\textsf{PL}\ v').truth
\end{array}
$$