

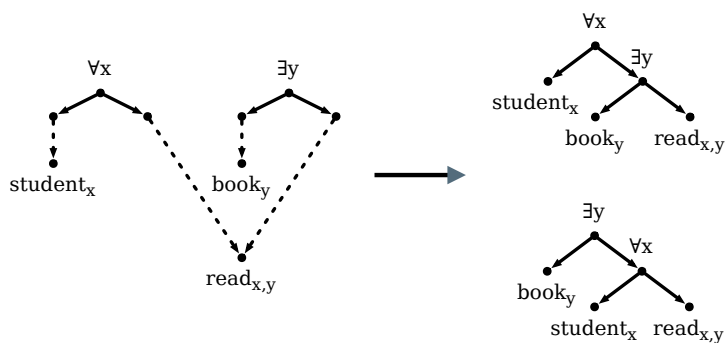
# Computational Linguistics

## Algorithms for Scope Underspecification

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### What this lecture is about



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### Overview

- Some basic assumptions about sentence meaning
- Scope ambiguities
- Modelling scope ambiguities with dominance graphs
- An algorithm for solving dominance graphs

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## Sentence meaning - Assumptions

- **Truth-functional interpretation:** The meaning of a declarative sentence is given by its truth conditions
- $\Rightarrow$  we can represent the meaning of natural language sentences by logical formula that "capture" the truth-conditions of the original sentence.
- *Every student works*  $\mapsto \forall x(\text{student}(x) \rightarrow \text{work}(x))$

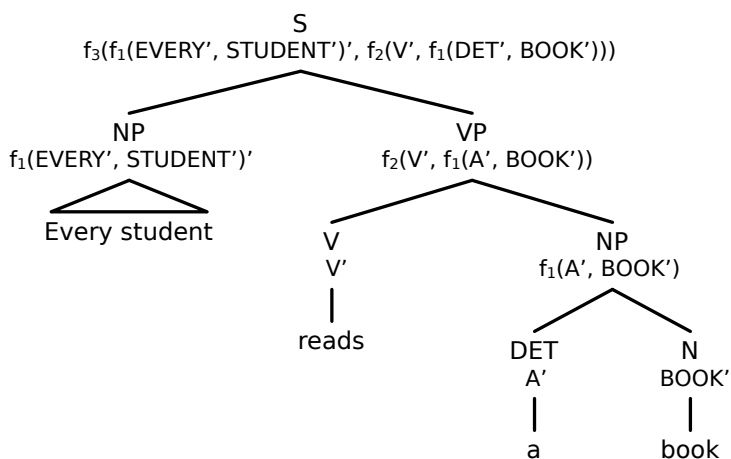
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## Sentence meaning - Assumptions

- **Compositionality:** The meaning of a complex expression is a function of the meanings of its parts and of the syntactic rules by which they are combined
- **Compositional semantic construction** based on the syntactic tree of the natural language expression
  - The semantic lexicon assigns meaning representations to lexical (leaf) nodes of the syntax tree.
  - The semantic representation of an inner node is computed by combining the representations of its child nodes.

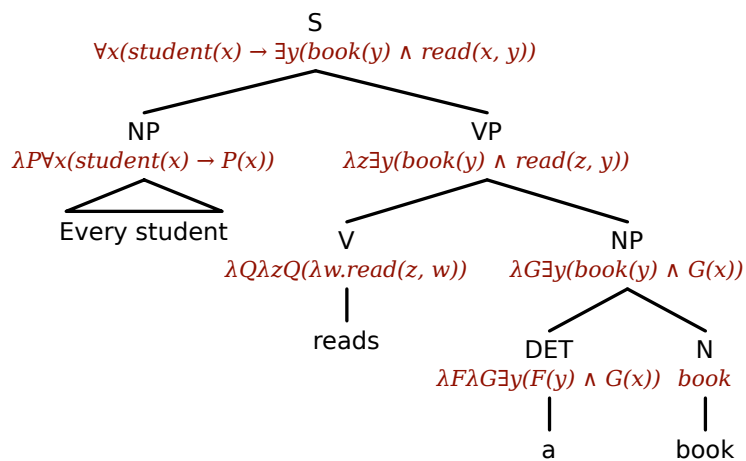
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## Compositional Semantics Construction



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## Compositional Semantics Construction



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## Compositional Semantics Construction

- Compositionality: The meaning of a complex expression is **a function** of the meanings of its parts and of the syntactic rules by which they are combined
- $\Rightarrow$  **Every syntax tree is mapped to a unique semantic representation**

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## Ambiguities

- Natural language is ambiguous: a sentence can have more than one interpretation ("reading").
- **Lexical ambiguities**
  - *Iraqi head seeks arms*
- **Structural ambiguities**
  - *Enraged cow injures farmer with axe*
  - *The salesman sold the dog biscuits*
  - *Every student reads a book*

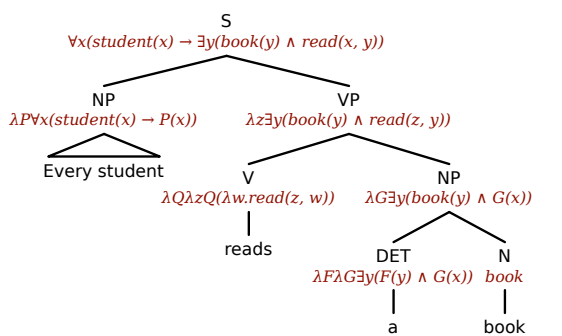
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# Scope Ambiguities

- Scope ambiguities can arise when a sentence contains two or more quantifiers and/or other scope-taking operators (negations, modal expressions, etc.)
- Every student reads a book*
  - $\forall x(\text{student}(x) \rightarrow \exists y(\text{book}(y) \wedge \text{read}(x, y)))$  [ $\forall\exists$ ]
  - $\exists y(\text{book}(y) \wedge \forall x(\text{student}(x) \rightarrow \text{read}(x, y)))$  [ $\exists\forall$ ]

## Scope Ambiguities - Problem #1

- The approach outlined before will give us just one reading (the “surface scope reading”)
- Problem:** How to compute the  $\exists\forall$  reading?



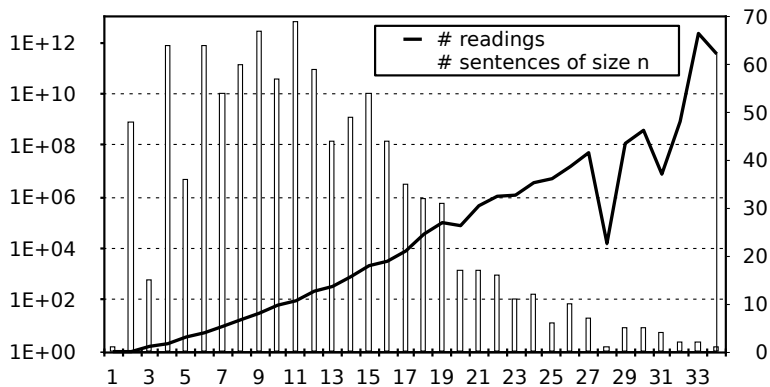
## Scope Ambiguities - Problem #2

- Combinatorial explosion of readings:** The number of readings of a sentence can grow exponentially in the number of scope-taking operators it contains.
- Every student reads a book*  $\Rightarrow$  2 readings
- Every student reads a book about an interesting topic*  $\Rightarrow$  5 readings (some of which are logically equivalent)
- We quickly put up the tents in the lee of a small hillside and cook for the first time in the open*  $\Rightarrow$  480 readings\* (most of which are logically equivalent)

\* according to the English Resource Grammar

## Scope Ambiguities – Problem #2

- Number of readings in a “real-live” corpus according to the English Resource Grammar (Koller & al., ACL 2008)



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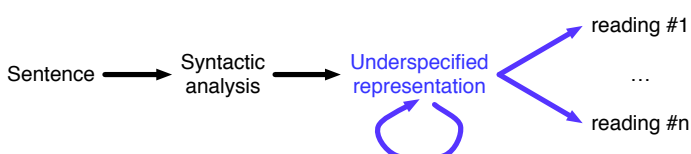
## Coping with scope – Options

- (1) Ignore scope ambiguities
  - for instance, always compute the “surface scope” reading
- (2) Enumerate all readings and then select the “right” one
  - we need more complex semantics construction rules and a method to choose the “right” reading
  - computationally very expensive, since sentences can easily have millions of readings
- (3) Use scope underspecification

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## Scope Underspecification

- Don't explicitly enumerate readings
- Instead, represent all readings of a sentence by a single compact underspecified representation (USR).
- The individual readings can be enumerated from the underspecified representation if needed (this lecture).
- We can perform inferences directly on the level of underspecified representations (next lecture).



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## A notational change

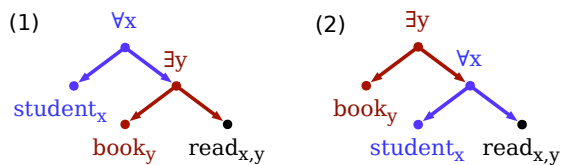
- *Every student reads a book*
  - $\forall x(\text{student}(x), \exists y(\text{book}(y), \text{read}(x, y)))$
  - $\exists y(\text{book}(y), \forall x(\text{student}(x), \text{read}(x, y)))$
- Abbreviations:
  - $\forall x(X, Y)$  abbreviates  $\forall x(X \rightarrow Y)$
  - $\exists x(X, Y)$  abbreviates  $\exists x(X \wedge Y)$

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## Readings = Trees

- *Every student reads a book*
  - (1)  $\forall x(\text{student}(x), \exists y(\text{book}(y), \text{read}(x, y)))$
  - (2)  $\exists y(\text{book}(y), \forall x(\text{student}(x), \text{read}(x, y)))$

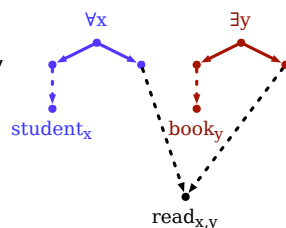
- Represent readings as trees:



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## Dominance Graphs (informal)

- Dominance graphs consist of
  - **“tree fragments”** connected by
  - **dominance edges**
- Tree fragments (solid lines) specify the “semantic material” that is common to all readings
- Dominance edges (dotted lines) specify constraints: The upper node must dominate the lower one.
- Subclass of “normal” dominance graphs: dominance edges always go from leaves (“holes”) to roots.



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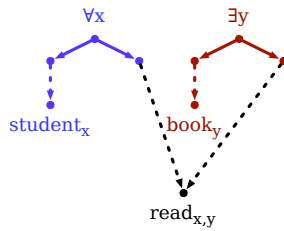
## Normal Dominance Graphs

■ A **normal dominance graph** is a graph  $G = \langle V, E \cup D \rangle$  such that

- the subgraph  $(V, E)$  is a collection of node disjoint trees where the height of each tree is  $\leq 1$

we call the roots in  $(V, E)$  **roots** and all other nodes **holes**

- if  $(v_1, v_2) \in D$ , then  $v_1$  is a hole and  $v_2$  a root
- every hole has at least one outgoing dominance edge.

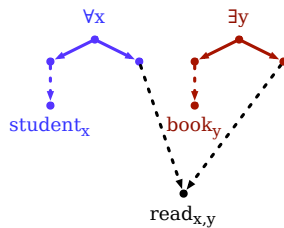


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## Normal Dominance Graphs

■ A **labelled dominance graph** is a graph  $\langle V, E \cup D, L \rangle$  such that

- $\langle V, E \cup D \rangle$  is a (normal) dominance graph and
- $L$  is a labelling function that assigns a node  $v$  a label with arity  $n$  iff  $v$  is a root with  $n$  outgoing tree edges



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## Solved Forms

- A dominance graph  $G$  is in **solved form** if  $G$  is a forest
- Let  $G = \langle V, E \cup D \rangle$  and  $G' = \langle V, E \cup D' \rangle$

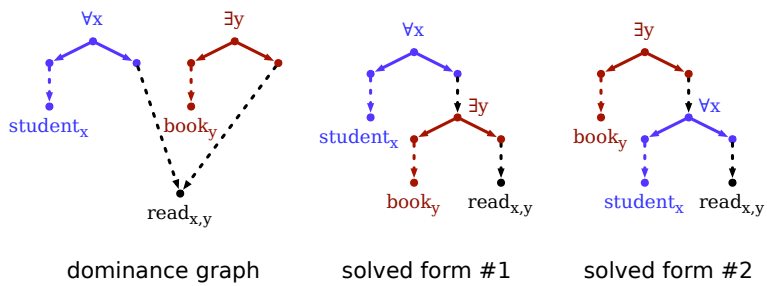
We say that  $G'$  is a **solved form of  $G$**  if  $G'$  is in solved form and the reachability relation of  $G'$  extends that of  $G$

That is: whenever  $v_1$  and  $v_2$  are connected by some dominance edge in  $G'$ , there must be a directed path from  $v_1$  to  $v_2$  in  $G$ .

- Note that dominance graphs and their solved forms differ only in their sets of dominance edges.
- Note also that the solved forms of connected dominance graphs are always trees.

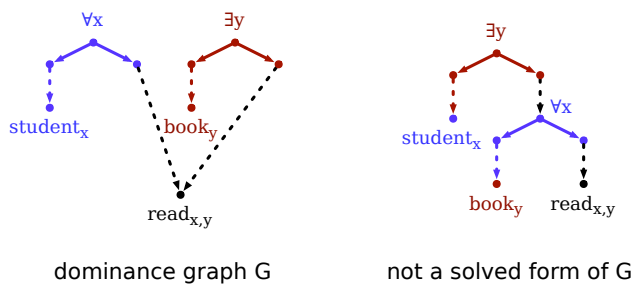
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## Solved Forms - Example



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## Not a solved form of



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## Computational Questions

- **The solvability problem:**  
Does a given dominance graph have any solved forms?
- **The enumeration problem:**  
Given a dominance graph, enumerate all its (minimal) solved forms.
- We will discuss the algorithm by Bodirsky & al. (2004)
- To keep things simple, we restrict the presentation to *connected* dominance graphs.

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## Solving dominance graphs

- The algorithm of Bodirsky &al. (2004) constructs a solved form of a dominance graph  $G$  as follows:
  1. nondeterministically choose a “free fragment”  $F$  from  $G$
  2. remove  $F$  from  $G$ ; this decomposes the graph  $G$  into weakly connected components  $G_1, \dots, G_k$
  3. recursively compute a solved form for  $G_1, \dots, G_k$
  4. attach the solved form of  $G_i$  under the corresponding hole of the free fragment  $F$  (for  $1 \leq i \leq k$ )

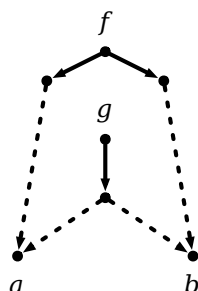
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## Free Fragments

- The workhorse of the algorithm is the notion of a “free fragment.”
- We say that a fragment  $F$  is **free in a** normal dominance graph  $G$  iff
  - the root of  $F$  has no incoming dominance edges, and
  - no distinct holes of  $F$  are connected by an undirected path in the graph  $G'$  obtained from  $G$  by removing the root of  $F$
- It can be shown that the following statements are equivalent if  $G$  is solvable (normal) dominance graph:
  - $F$  is a free fragment in  $G$
  - $G$  has a solved form with top-most fragment  $F$

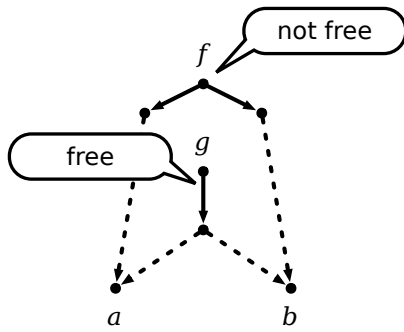
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## Free Fragments: An Example



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# Free Fragments: An Example



(Bodirsky & al., 2004)

# Solving dominance graphs

**solve**( $G = (V, E \cup D)$ ) = (\*)

**choose** a free fragment  $F$  of  $G$  **else fail**

let  $G_1, \dots, G_k$  be the WCCs of  $G \setminus F$

let  $(V_i, E_i \cup D_i) = \text{solve}(G_i)$

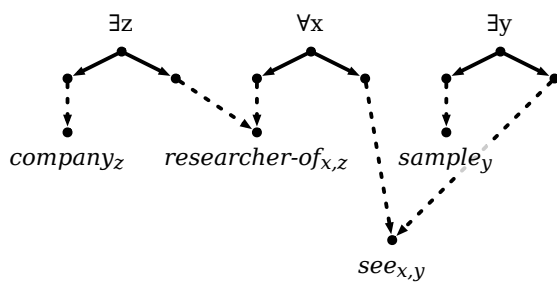
**return**  $(V, E \cup D_1 \cup \dots \cup D_k \cup D')$

where  $D'$  are dominance edges that connect the holes of  $F$  with the solved form of one of the corresponding  $G_i$

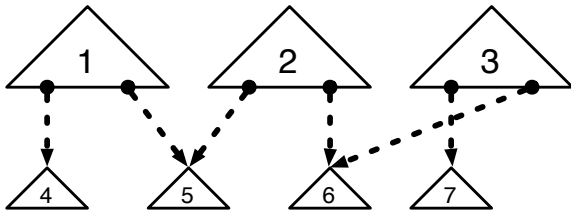
(\*) slightly simplified version, works only for connected normal dominance graphs

# An Example

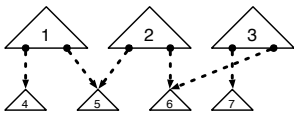
- Underspecified representation for the sentence "every researcher of a company sees a sample:"



# An Example

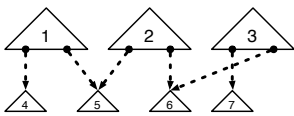


# An Example

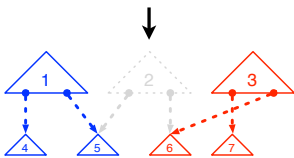


subgraph	free	wccs

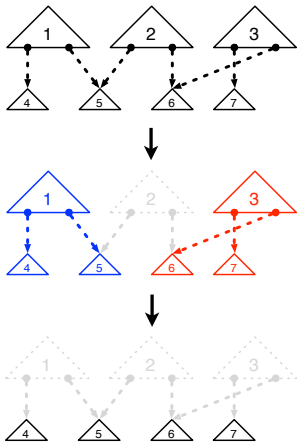
# An Example



subgraph	free	wccs
{1,...,7}	2	{1,4,5}, {3,6,7}



## An Example

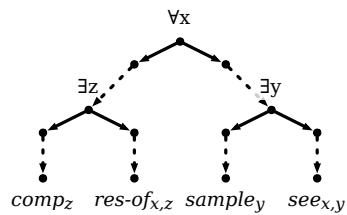


subgraph	free	wccs
{1,...,7}	2	{1,4,5}, {3,6,7}
{1,4,5}	1	{4}, {5}
{3,6,7}	3	{6}, {7}

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## The final solved form

- $\forall x(\exists z(\text{comp}(z), \text{res-of}(x,z)), \exists y(\text{sample}(y), \text{see}(x, y)))$



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## Properties of the solver

- It can be shown that the following statements are equivalent:
  - solve(G) fails for some nondeterministic choice
  - G is not solvable
  - solve(G) fails for all nondeterministic choices

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## Properties of the solver

- We can test whether a fragment is free in time  $O(n + m)$ 
  - where  $n$  is the number of nodes and
  - $m$  the number of edges in a dominance graph  $G$ .
- The overall running time of  $\text{solve}(G)$  is in  $O(n \cdot (n + m))$  per solved-form.

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## Literature

- Alexander Koller, Manfred Pinkal, and Stefan Thater. Scope Underspecification with Tree Descriptions: Theory and Practice [PDF]. In: Resource Adaptive Cognitive Processes. Ed. by Matthew Crocker and Jörg Siekmann. Cognitive Technologies Series. Berlin: Springer. 2009.
- Manuel Bodirsky, Denys Duchier, Joachim Niehren, and Sebastian Miele (2004). A new algorithm for normal dominance constraints [PDF]. In the proceedings of the Symposium on Discrete Algorithms (SODA04), 59-67.

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