Semantic Theory

Underspecification

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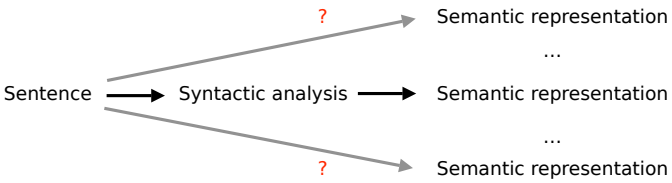
Scope ambiguities

- Sentences with two or more scope bearing operators such as quantifiers, negations, ... are often ambiguous:
- "Every student presents a paper."
  - $\forall x(\text{student}'(x) \rightarrow \exists y(\text{paper}'(y) \wedge \text{present}'(x,y)))$
  - $\exists y(\text{paper}'(y) \wedge \forall x(\text{student}'(x) \rightarrow \text{present}'(x,y)))$
- "Every student didn't pay attention."
  - $\forall x(\text{student}'(x) \rightarrow \neg\text{pay-attention}'(x))$
  - $\neg\forall x(\text{student}'(x) \rightarrow \text{pay-attention}'(x))$

Scope Ambiguities: Problem #1

- Compositional semantic construction: the readings are determined by the syntactic structure.
- How can we derive more than one reading if the sentence has only one syntactic structure?



Nested Cooper Storage

- "Every student presents a paper."
  - $\langle \text{present}^*(x_2)(x_1), \{$
    $\langle \lambda P\, \forall x[\text{student}'(x) \rightarrow P(x)], \emptyset\rangle_1,$ $[= \langle \text{ES}, \emptyset\rangle_1]$
    $\langle \lambda Q\, \exists y[\text{paper}'(y) \wedge Q(y)], \emptyset\rangle_2 \quad \}\rangle$ $[= \langle \text{AP}, \emptyset\rangle_2]$
- Retrieval:
  1. $\text{ES}(\lambda x_2(\text{AP}(\lambda x_1(\text{present}^*(x_2)(x_1)))))$
     $\Rightarrow_\beta \exists y(\text{paper}'(y) \wedge \forall x(\text{student}'(x) \rightarrow \text{present}^*(y)(x)))$
  2. $\text{AP}(\lambda x_1(\text{ES}(\lambda x_2(\text{present}^*(x_2)(x_1)))))$
     $\Rightarrow_\beta \forall x(\text{student}'(x) \rightarrow \exists y(\text{paper}'(y) \wedge \text{present}^*(y)(x)))$

Nested Cooper Storage

- Storage techniques like Nested Cooper Storage allow to derive several distinct readings on the basis of a single syntactic analysis.
  - Problem #1 solved (… to a certain extent)
- But note that Nested Cooper Storage has its own problems:
  - Non-determinism (storage vs. application)
  - For certain types of sentences it is not possible to derive all reading (e.g., “every student did not pay attention.”)

Scope Ambiguities: Problem #2

- Combinatorial explosion of readings: the number of readings can grow exponentially with the number of scope bearing operators.
  - “Most politicians can fool most voters on most issues most of the time, but no politician can fool every voter on every single issue all of the time.”
    (ca. 600 readings, Hobbs)
  - “But that would give us all day Tuesday to be there.”
    (ca. 65000 readings according to the ERG)

Enumeration of Readings is sometimes not necessary

- Some sentences can be evaluated semantically without having to commit to one scope reading:
  - “In Saarbrücken, many scientists at several institutes are working on numerous interesting research problems in different areas of semantics.”
  - “Every student must speak two foreign languages. This is definitely too much.”

Immediate Enumeration of Readings is not always necessary

- The disambiguation to one reading can occur naturally as the discourse progresses:
  - “Every student must speak two foreign languages. These languages are taught at our department.”
  - “Every student must speak two foreign languages. Appendix 1 of the Studienordnung lists the twenty admissible languages.”

Enumeration of Readings is not always necessary

- Sentences can contain “spurious ambiguities”
  - “We quickly put up the tents in the lee of a small hillside and cook for the first time in the open.”
  - 480 readings according to the English Resource Grammar …
  - but only 2 equivalence classes, characterised by the relative scope of “the lee of” and “a small hillside”

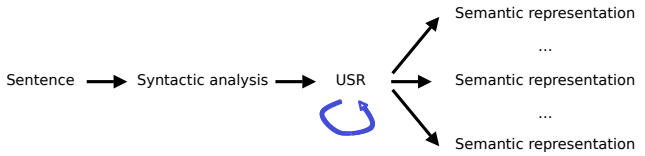
Disambiguating Factors

- World knowledge can exclude some readings:
  - “A rabbit is in every hat.”
  - “She has a finger in every pie.”
- Preferences, such as
  - Word order
  - Intonation
  - Choice of determiners: “a search engine for every subject” vs. “a search engine for each subject”
  - (from Language Log: A quantifier for every season)

So where do we stand?

- By using storage techniques, we can compute the readings of scopally ambiguous sentences compositionally.
- But …
  - the number of readings can grow exponentially with the number of scope-bearing elements.
  - enumerating all readings can thus take a long time.
  - most of this time is wasted.

Underspecification: the big picture



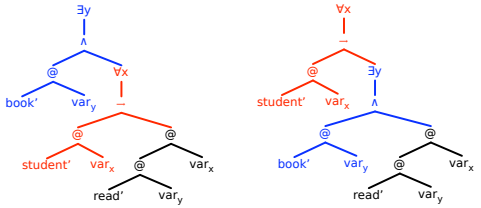
- Derive a single underspecified semantic representation (USR) from the syntactic analysis.
- Perform inferences on USR to eliminate readings excluded by the context.
- Enumerate readings by need.

Scope Underspecification

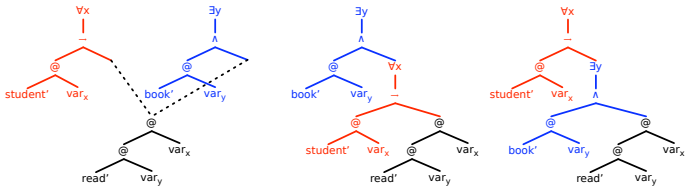
- Basic observation:
  - The readings of scopally ambiguous sentences are made up of the same set of constants, connectives and variables, and differ only in their structure
  - "Every student reads a book."
    - ∀x(student'(x) → ∃y(book'(y) ∧ read'(x,y)))
    - ∃y(book'(y) ∧ ∀x(student'(x) → read'(x,y)))
- Basic idea:
  - Consider semantic representations as trees
  - Describe sets of trees using dominance graphs

Scope Underspecification: the Idea

- "Every student reads a book"
  - ∀x(student'(x) → ∃y(book'(y) ∧ read'(y)(x)))
  - ∃y(book'(y) ∧ ∀x(student'(x) → read'(y)(x)))
- Readings as trees:



Scope Underspecification: the Idea



(USR) (Readings as trees)

Outline

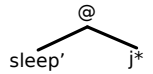
- Terms as trees
- Dominance graphs as descriptions of sets of trees
- Semantics construction with dominance graphs
- Things you can do with dominance graphs

Terms as Trees

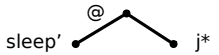
- Terms (and formulas) of type theory have a natural reading as trees:
  - Application M(N) is the tree @(M,N)
  - Abstraction λx.M is the tree lam(M)
    - Quantifiers analogously
  - Constant symbols correspond to leaf labels
  - Variables x correspond to leaves with label var_x.
    - (Alternatively: binding edges, see slides at the end)

Terms as Trees

- sleep'(j*)

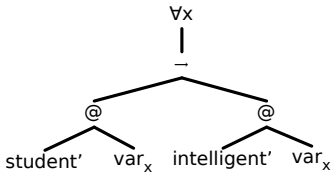


- Alternative notation
  (used later for semantics construction)



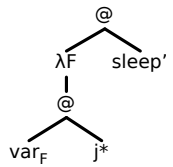
Terms as Trees

- ∀x(student'(x) → intelligent'(x))



Terms as Trees

- (λF.F(j*))(sleep')

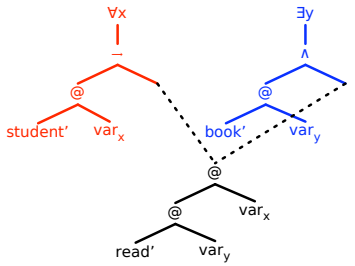


Dominance Graphs

- Informally, a dominance graph is a directed graph which consists of trees (or “tree fragments”) which are connected by dominance edges.
- For modeling scope underspecification, we consider labeled dominance graphs, i.e. pairs of a dominance graph and a partial node labeling function L
  - L must be defined on all non-leaves of the tree fragments
  - Leaves may be unlabelled
- Terminology:
  - Unlabeled leaves are called “holes”
  - Nodes without incoming tree edges are called “roots”

An Example

- Three tree fragments that informally correspond to
  - ∀x(student’(x) → …)
  - ∃y(book’(y) ∧ …)
  - read(y)(x)
- The two upper fragments each have one hole.
- The holes have outgoing dominance edges to the root of the lower fragment.



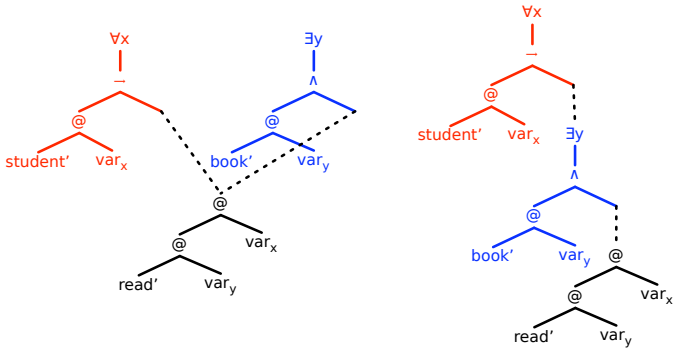
Dominance Graphs

- More formally, a dominance graph is defined as a directed graph G = (V, E ∪ D) where V is a set of nodes and
  - E is a set of “tree edges” (solid edges)
  - D is a set of “dominance edges” (dotted edges)
- The subgraph (V, E) must be a forest, i.e. it is acyclic and no node has more than one incoming (tree-) edge.
- Labelled dominance graphs: G = (V, E ∪ D, L) where L is a partial labelling function mapping nodes in V to labels of some signature Σ.

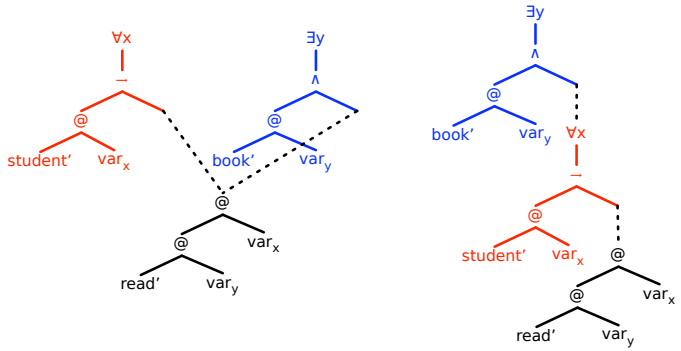
Solved Forms

- A dominance graph G can be seen as a description of a set of trees into which G can be embedded.
- These trees can be represented by the solved forms of G.
- A dominance graph G_S is said to be in solved form if it is a forest, i.e. no node has more than one incoming dominance edge.
- G_S is a solved form of some dominance graph G if
  - G_S is in solved form
  - G_S and G differ at most in their dominance edges, and
  - if nodes X and Y are connected by a dominance edge in G, then there is a directed path from X to Y in G_S.

An Example

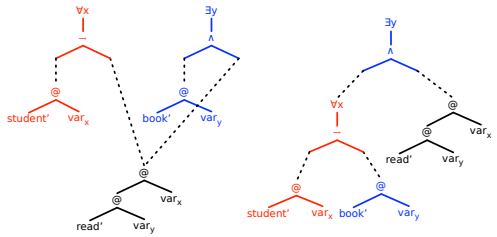


An Example



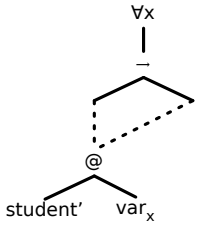
Not a solved form of ...

- The dominance graph on the right is in solved form, but it is not a solved form of the graph on the left
  - the dominance edge from the ∀-fragment to the read-fragment is not realised as reachability in the right graph



An unsolvable graph

- Not all dominance graphs have a solved form

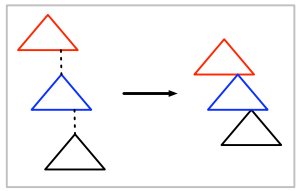


Solved Forms – Remark #1

- As said earlier, the solved forms of a dominance graph G represent the trees into which G can be embedded.
  - (these trees are the solutions of G)
- For modeling scope underspecification, we are usually interested in a particular class of solutions called constructive solutions.
- Not every solved form corresponds to a constructive solution, but recent studies indicate that the solved forms of all "linguistically relevant" graphs all correspond to constructive solutions.

Solved Forms – Remark #1

- Basic idea: if each hole of a solved form has exactly one outgoing dominance edge, ...
- then one can obtain a constructive solution by identifying the two ends of each dominance edge.



Solved Forms – Remark #2

- We can distinguish various sub-classes of dominance graphs, depending on which kinds of dominance edges are permitted
  - In normal dominance graphs, dominance edges are only permitted between holes and roots.
  - Weakly normal dominance graphs additionally permit root-to-root dominance edges (but not hole-to-root edges)
- Note that for dominance graphs with hole-to-root dominance edges, we need a more general definition of a solved form.
- (The graphs considered in this lecture are all normal)

Where are we now?

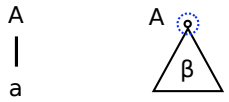
- Formulas (readings of natural language sentences) can be seen as trees.
- These trees can be described by dominance graphs ...
- in the sense that the solved forms of a graph correspond to the readings of the underlying sentence.
- Next step: Semantic construction for dominance graphs.

Semantics Construction: Principles

- For every node in the syntax tree, we derive a dominance graph as follows:
  - Each syntax rule is associated with a semantics rule that combines dominance graphs.
  - Each of these sub-dominance graphs has an interface node that is used to connect it with other subgraphs.
  - The USR for the whole sentence is then the dominance graph associated with the root of the sentence.

Lexicon access

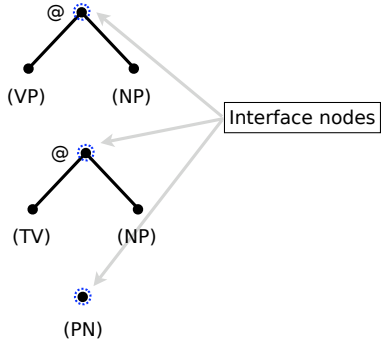
- Rule of lexical nodes:



The semantic representation (sub-graph) β for a word “a” is supplied by the lexicon.

Semantics construction rules

- S → NP VP
- VP → TV NP
- NP → PN



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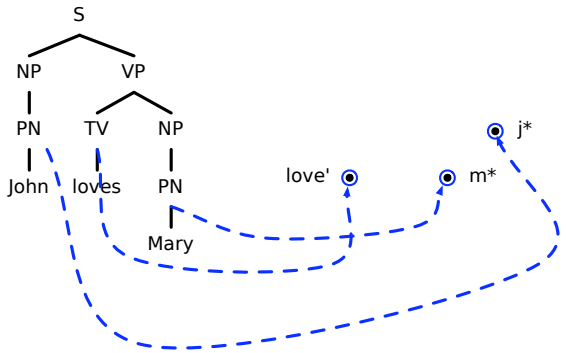

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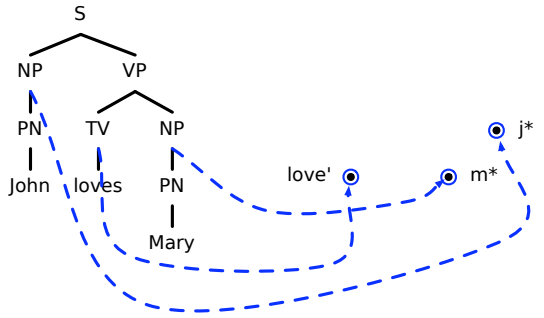

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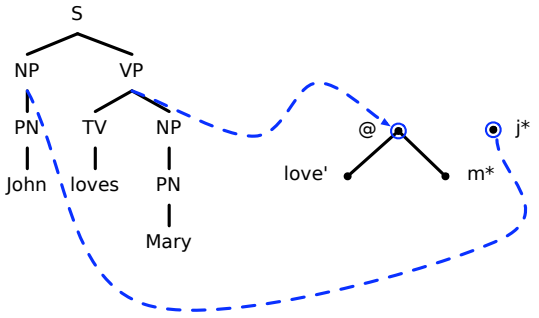

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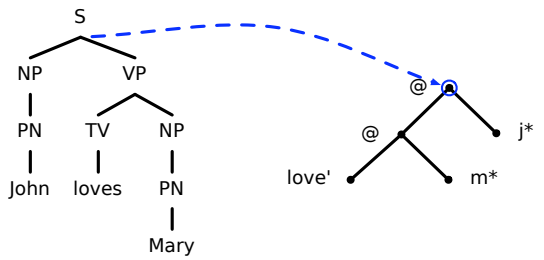
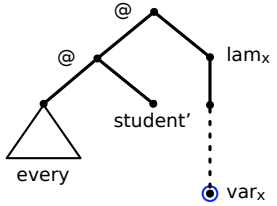


Semantic representation: love'(m*)(j*)

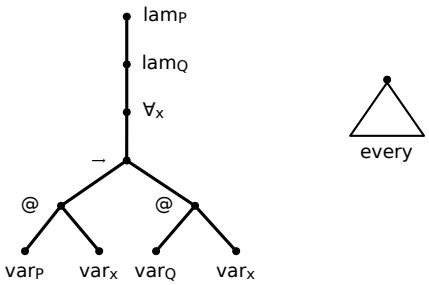
Quantifiers

- The graph for a quantifier noun phrase contains a variable node and its binder.
- The interface node of the graph is the node that represents the variable (of type e)



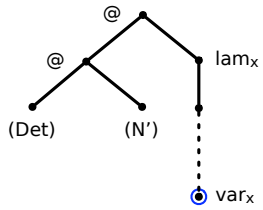
Constructing Graphs for Quantifiers

- Lexicon entry for determiners (here “every”):



Constructing Graphs for Quantifiers

- Syntax rule: NP → Det N’



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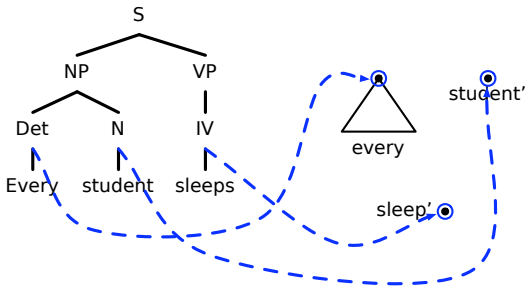

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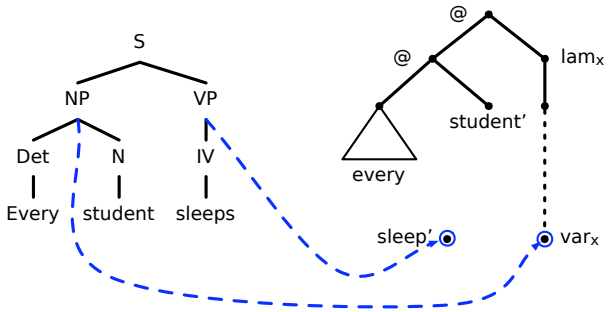

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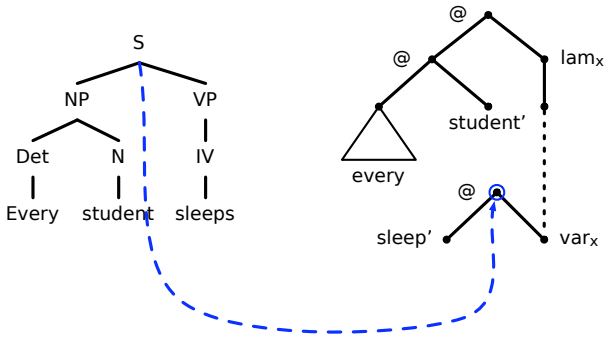
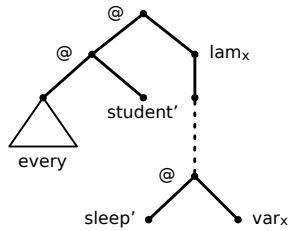


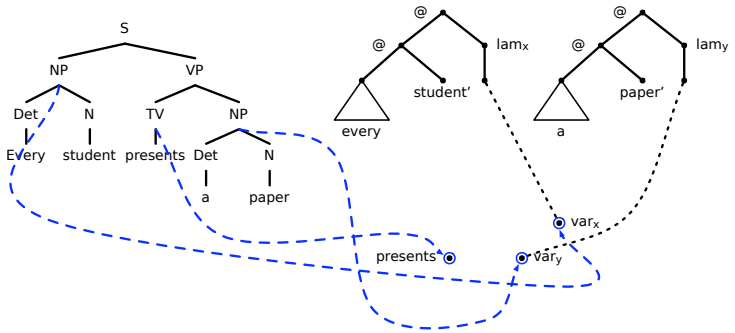
After "Normalisation"

- In a final step, we replace dominance edges pointing into fragments by dominance edges pointing to the root of the fragment.



- Corresponding formula:
  - $(\lambda P \lambda Q \forall y[P(y) \rightarrow Q(y)])(\text{student}')(\lambda x\ \text{sleep}'(x))$
  - $\Rightarrow_\beta \forall y[\text{student}'(y) \rightarrow \text{sleep}'(y)]$

Scope Ambiguities



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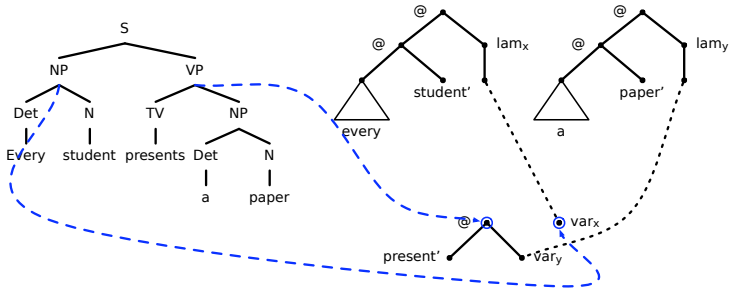

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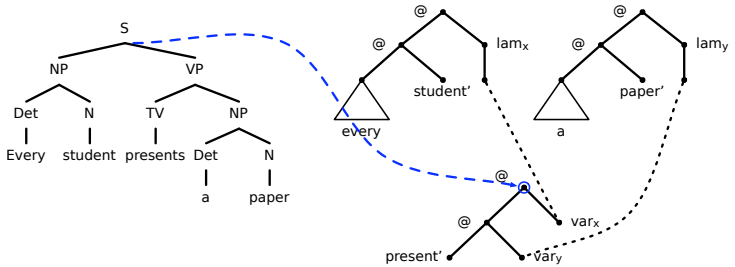

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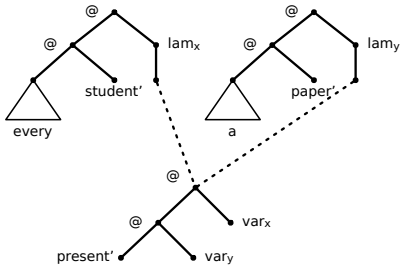


An observation

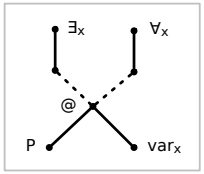
- We still use type theory as the object language, i.e. the language of semantic representations.
- However, types no longer drive the construction process.
- We use far fewer lambdas for “construction bookkeeping”; we replace this by plugging USRs into each other directly.
- This makes us more flexible in our choice of semantic representations:
  - can use john* of type e for proper names
  - can use present* of type ⟨e,⟨e,t⟩⟩ for transitive verbs

An observation about NPs

- The quantifier representation is split into two parts:
  - a variable of type e which the verb is applied to; this is like the x_i that is introduced in the Nested Cooper Storage rule.
  - a fragment containing a quantifier representation of type ⟨⟨e,t⟩,t⟩, which is applied at some point to what would be the “semantic content” in Nested Cooper Storage.
- The two components are connected by binding and dominance edges.
- The variable binding is introduced together with the variable and the binder; no need for “variable capturing.”

Representing variable binding

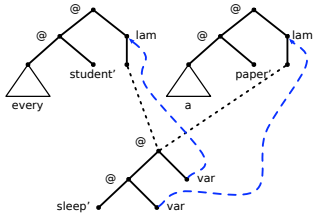
- As in type theory, we use variable names to model the relation between a binder (λ, ∀, ∃) and the variables bound by it.
- In an underspecification context, variable names aren't always sufficient to indicate the binder for each variable:



- Problem could be solved by requiring that variables are named apart.
- Binding edges are a cleaner and simpler way of doing it.

Using binding edges

- Assume a third type of edges: binding edges
- All variables have label "var," and labels representing lambda-binders as "lam" (quantifiers analogously)
- The graph for "every student presents a paper" with binding edges:



Things one can do with dominance graphs

- Deciding solvability
  - given a dominance graph G, has G as solved form?
- Enumerating solved forms
  - given a dominance graph G, enumerate the (minimal) solved forms of G.
- Eliminating redundant readings
  - Strengthen an USR G such that it has fewer readings, but still contains a representative for each equivalence class of G.

Other Formalisms

- Dominance constraints
  - Logical descriptions of trees
  - Important fragments: normal and weakly normal dominance constraints
- Minimal Recursion Semantics
  - Similar to weakly normal dominance constraints (or graphs)
  - Standard underspecification formalism used in HPSG
- Hole Semantics
- Glue Semantics
- (and many more …)

Relation to dominance graphs

- Weakly normal dominance graphs are equivalent to weakly normal dominance constraints.
- Important subsets of both Minimal Recursion Semantics and Hole Semantics can be translated into (normal) dominance graphs
  - Restriction: the USRs must have certain structural properties
  - Conjecture: all USRs needed to model scope underspecification have these properties.

Conclusion

- Enumerating all readings is typically a waste of time.
- Underspecification: Enumerate only by need.
- Dominance graphs: Encode readings as trees; use graphs as underspecified semantic representations.
- Simple semantics construction that combines sub-dominance graphs.
- Each syntactic combination rule is associated with a semantic combination rule.