# Semantic Theory

## Lecture 5: Scope ambiguities

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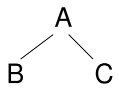
## The story so far

- We want:
  - logic-based semantic representations that capture the truth conditions of a sentence
    - type theory, tense & modal logic, ...
  - compositional semantics construction
    - lambdas
- This works pretty well up to this point!
- And we could envisage that the system could be conservatively extended to deal with the rest of semantics too.

## Some basic rules

- Rule of functional application:




$$\frac{B \Rightarrow \beta: \langle\sigma, \tau\rangle \quad C \Rightarrow \gamma:\sigma}{A \Rightarrow \beta(\gamma): \tau} \quad \text{or} \quad \frac{B \Rightarrow \beta: \sigma \quad C \Rightarrow \gamma: \langle\sigma, \tau\rangle}{A \Rightarrow \gamma(\beta): \tau}$$

- Rule of non-branching nodes:


$$\frac{B \Rightarrow \beta: \tau}{A \Rightarrow \beta: \tau}$$



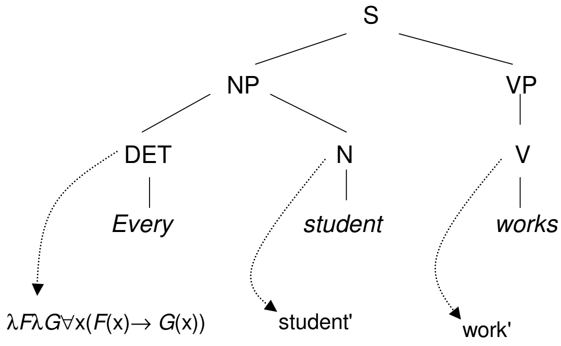
## Some basic rules

- Rule of lexical nodes:


$$\frac{}{A \Rightarrow \beta: \tau}$$

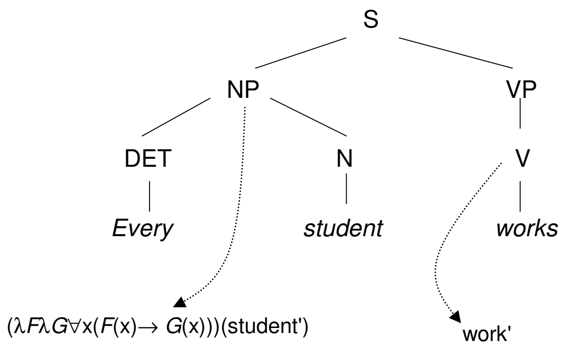
The semantic representation β for the word "a" is supplied by the lexicon.

# An example



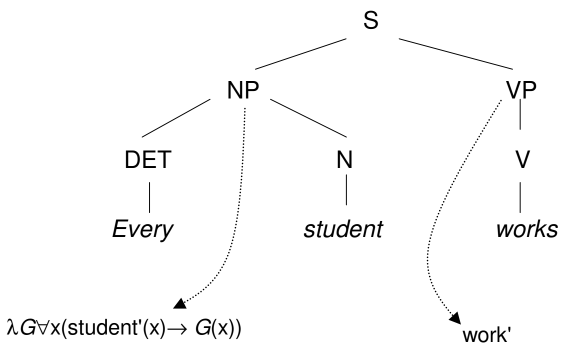



# An example



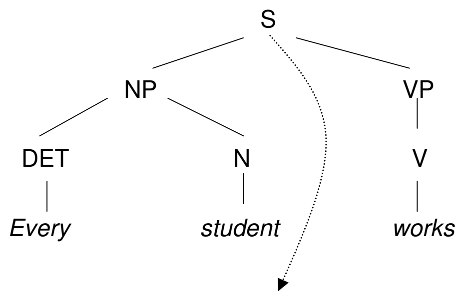

$\Leftrightarrow_\beta$ $\lambda G \forall x(\text{student}'(x) \rightarrow G(x))$

# An example






# An example




$(\lambda G \forall x(\text{student}'(x) \rightarrow G(x)))(\text{work}')$

$\Leftrightarrow_\beta \forall x(\text{student}'(x) \rightarrow \text{work}(x))$

# However ...

- ... perhaps we made an assumption that is not generally correct!



# What does this mean?

- "Now we've got at least one city with all seven religions."

## What does this mean?

- Headline: "A search engine for every subject"

  (see: http://itre.cis.upenn.edu/~myl/languagelog/archives/002835.html)



## What does this mean?

- "Every linguist speaks two languages."
  - the same set of languages for each linguist?

## What does this mean?

- "During his visit to China, Helmut Kohl intends to visit a factory for CFC-free refrigerators."
  - are there concrete plans for a particular factory?
  - are there factories for CFC-free refrigerators in China?



## What do all these mean?

- "Victoria refuses to trade all her techs."
- "The bishop sent a letter to all priests."
- "It just didn't occur to me that a Barracks might not be there!"

## Scope ambiguities

- Some sentences have more than one possible semantic representation:

  Every student presents a paper.

  (a) $\forall x[\textit{student}'(x) \to \exists y[\textit{paper}'(y) \wedge \textit{present}'(x,y)]]$

  (b) $\exists y[\textit{paper}'(y) \wedge \forall x[\textit{student}'(x) \to \textit{present}(x,y)]]$

  Every student didn't pay attention.

  (a) $\forall x[\textit{student}'(x) \to \neg \textit{pay-attention}'(x)]$

  (b) $\neg \forall x[\textit{student}'(x) \to \textit{pay-attention}'(x)]$



## Scope ambiguities

- The number of readings of a sentence with scope ambiguities grows with the number of NPs:

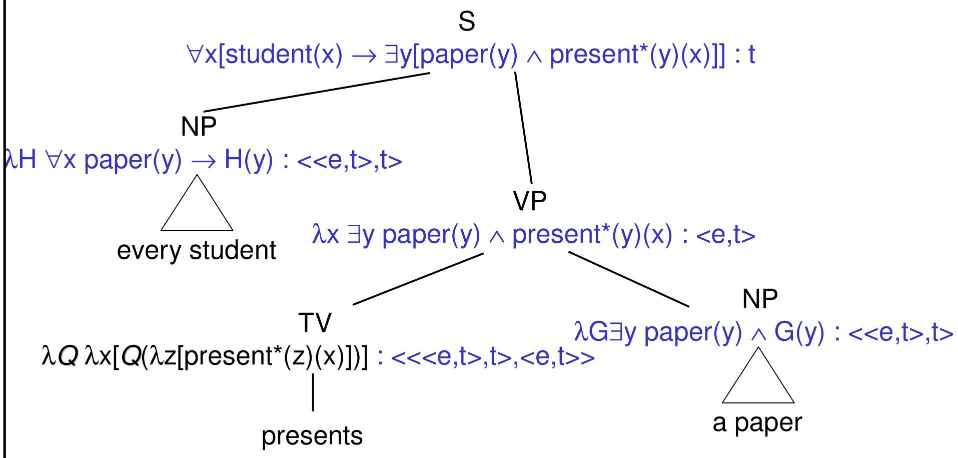
  Every researcher of a company saw some sample.

  1. $\forall x(res'(x) \wedge \exists y(cp'(y) \wedge of'(x,y)) \to \exists z(spl'(z) \wedge see'(x,z))$
  2. $\exists z(spl'(z) \wedge \forall x(res'(x) \wedge \exists y(cp'(y) \wedge of'(x,y)) \to see'(x,z))$
  3. $\exists y(cp'(y) \wedge \forall x(res'(x) \wedge of'(x,y)) \to \exists z(spl'(z) \wedge see'(x,z))$
  4. $\exists y(cp'(y) \wedge \exists z(spl'(z) \wedge \forall x(res'(x) \wedge of'(x,y)) \to see'(x,z))$
  5. $\exists z(spl'(z) \wedge \exists y(cp'(y) \wedge \forall x(res'(x) \wedge of'(x,y)) \to see'(x,z))$

  Every researcher of a company saw some samples of most products.

  etc.

## But: We get only one reading!

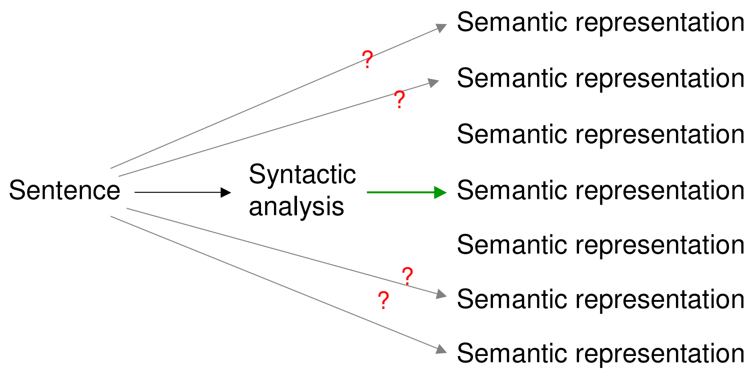





## The problem with scope

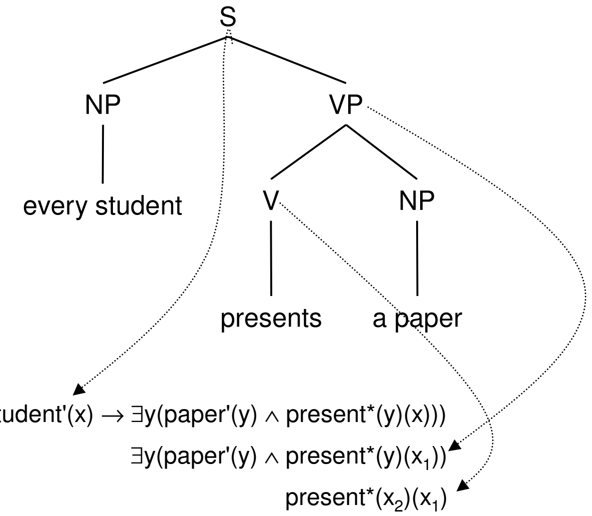
- Sentences with scope ambiguities can have multiple semantic representations for a syntactic constituent.
- The order of the scope-bearing elements (quantifiers, negation, adverbs, ...) don't necessarily follow the order of the syntactic combination.
- But: With the approach we have so far, we can only derive a single semantic representation for each constituent!
- How can we solve this problem?

# Semantic ambiguity: A picture






# Solving the scope problem: Intuition




$$\forall x(student'(x) \rightarrow \exists y(paper'(y) \wedge present^*(y)(x)))$$

$$\exists y(paper'(y) \wedge present^*(y)(x_1))$$

$$present^*(x_2)(x_1)$$

## The missing reading

- We get one reading of the sentence by deriving the following terms:

$$\forall x(\text{student}'(x) \to \exists y(\text{paper}'(y) \wedge \text{present}^*(y)(x)))$$
$$\exists y(\text{paper}'(y) \wedge \text{present}^*(y)(x_1))$$
$$\text{present}^*(x_2)(x_1)$$

- We could construct the second reading as follows:

$$\exists y(\text{paper}'(y) \wedge \forall x(\text{student}'(x) \to \text{present}^*(y)(x)))$$
$$\forall x(\text{student}'(x) \to \text{present}^*(x_2)(x))$$
$$\text{present}^*(x_2)(x_1)$$



## Solving the scope problem: Principles

- Structural ambiguity: We can obtain the two readings by embedding an intermediate term into the NP representations in different orders.
- Invariant variable binding: At the same time, we must make sure that the variables will be bound in the same way in both readings.
- To a certain degree, we can solve both problems using lambda abstraction in a clever way.

## Using lambda abstraction ("Montague's Trick")

- Intermediate results are all of type t. Abstract over the correct variable and then apply the NP representation to the abstracted term.

$$\lambda F \forall x(student'(x) \rightarrow F(x))(\lambda x_1.\ \lambda G \exists y(paper'(y) \wedge G(y))(\lambda x_2.present^*(x_2)(x_1)))$$
$$\lambda G \exists y(paper'(y) \wedge G(y))(\lambda x_2.present^*(x_2)(x_1))$$
$$present^*(x_2)(x_1)$$

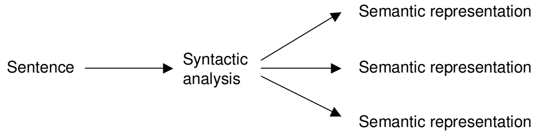
$$\lambda G \exists y(paper'(y) \wedge G(y))(\lambda x_2.\ \lambda F \forall x(student'(x) \rightarrow F(x))(\lambda x_1.present^*(x_2)(x_1)))$$
$$\lambda F \forall x(student'(x) \rightarrow F(x))(\lambda x_1.present^*(x_2)(x_1))$$
$$present^*(x_2)(x_1)$$

- Problem: How can we do this compositionally?



## Nested Cooper Storage

- One algorithm for deriving such representations compositionally is Nested Cooper Storage (Keller 1988). It repairs some problems of the original Cooper Storage (Cooper 1975).
- Cooper Storages compute the set of all semantic readings nondeterministically from a single syntactic analysis:



## Nested Cooper Storage: Principles

- The semantic values of syntactic constituents are ordered pairs $\langle\alpha, \Delta\rangle$:
  - $\alpha \in WE_\tau$ is the content
  - $\Delta$ is the quantifier store: a set of NP representations that must still be applied.
- At NP nodes, we may store the content in $\Delta$.
- At sentence nodes, we can retrieve NP representations from the store in arbitrary order and apply them to the appropriate argument positions.

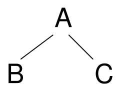


## Nested Cooper Storage: Principles

- A syntactic constituent may be associated with multiple semantic values of this form.
- A lambda term M counts as a semantic representation for the entire sentence iff we can derive $\langle M, \varnothing\rangle$ as a value for the root of the syntax tree.
- Hence, there may be more than one valid semantic representation for the complete sentence.

## Nested Cooper Storage: Old Rules

- Rule of functional application:




$$\frac{B \Rightarrow \langle \beta, \Delta \rangle \quad C \Rightarrow \langle \gamma, \Gamma \rangle}{A \Rightarrow \langle \beta(\gamma), \Delta \cup \Gamma \rangle} \quad \text{or} \quad \frac{B \Rightarrow \langle \beta, \Delta \rangle \quad C \Rightarrow \langle \gamma, \Gamma \rangle}{A \Rightarrow \langle \gamma(\beta), \Delta \cup \Gamma \rangle}$$

- Rule of non-branching nodes:


$$\frac{B \Rightarrow \langle \beta, \Delta \rangle}{A \Rightarrow \langle \beta, \Delta \rangle}$$

- Rule of lexical nodes:


$$\frac{}{A \Rightarrow \langle \beta, \varnothing \rangle}$$



## Nested Cooper Storage: Storage

$$\frac{B \Rightarrow \langle \gamma, \Gamma \rangle \qquad \text{B is an NP node}}{B \Rightarrow \langle \lambda P.P(x_i), \{\langle \gamma, \Gamma \rangle_i\} \rangle \qquad \text{where } i \in \mathbf{N} \text{ is a new index}}$$

- Using this rule, we can assign more than one semantic value to an NP node.
- The content of the new semantic value is just a placeholder of type <<e,t>,t>, and the old value (including its store) is moved to the store.

## Nested Cooper Storage: Retrieval

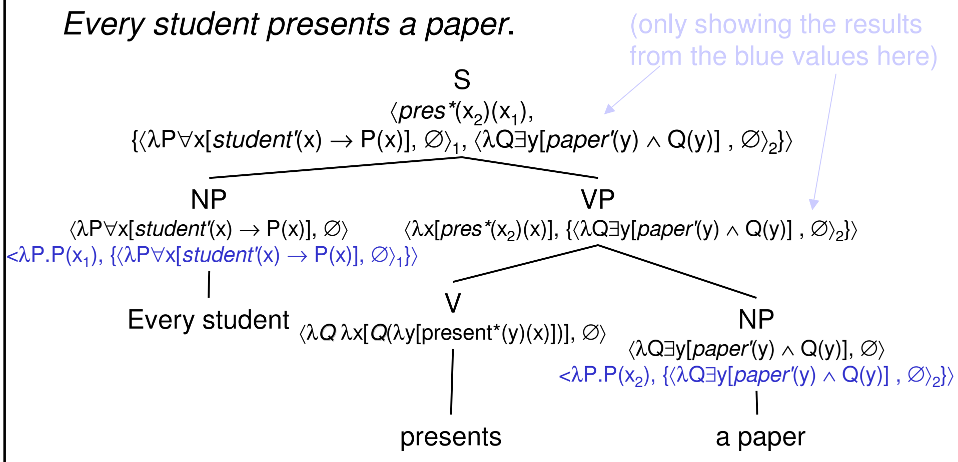
$$\frac{A \Rightarrow \langle \alpha, \Delta \cup \{\langle \gamma, \Gamma \rangle_i\} \rangle}{A \Rightarrow \langle \gamma(\lambda x_i \alpha), \Delta \cup \Gamma \rangle} \quad \text{A is any sentence node}$$

- Using this rule, we can apply a stored NP.
- At this point, the correct $\lambda$-abstraction for the variable associated with the stored element is introduced.
- The old store $\Gamma$ is released into the store for A.
- This implements Montague's Trick.



## Nested Cooper Storage: Example

*Every student presents a paper.*



## Retrieval: Reading 1

- By applying the Retrieval rule, we can derive the following representation for the S node:

$\langle$*pres*$^*(x_2)(x_1)$, $\{\langle \lambda P \forall x[$*student'*$(x) \rightarrow P(x)], \varnothing\rangle_1, \langle \lambda Q \exists y[$*paper'*$(y) \wedge Q(y)], \varnothing\rangle_2\}\rangle$

$\Rightarrow_R \langle \lambda Q \exists y[paper'(y) \wedge Q(y)](\lambda x_2.pres^*(x_2)(x_1)),$
$\{\langle \lambda P \forall x[student'(x) \rightarrow P(x)], \varnothing\rangle_1\}\rangle$

$\Rightarrow_\beta \langle \exists y[paper'(y) \wedge pres^*(y)(x_1)], \{\langle \lambda P \forall x[student'(x) \rightarrow P(x)], \varnothing\rangle_1\}\rangle$

$\Rightarrow_R \langle \lambda P \forall x[student'(x) \rightarrow P(x)](\lambda x_1.\exists y[paper'(y) \wedge pres^*(y)(x_1)]), \varnothing\rangle$

$\Rightarrow_\beta \langle \forall x[student'(x) \rightarrow \exists y[paper'(y) \wedge pres^*(y)(x)]], \varnothing\rangle$



## Retrieval: Reading 2

- By applying the Retrieval rule, we can derive the following representation for the S node:

$\langle pres^*(x_2)(x_1), \{\langle \lambda P \forall x[student'(x) \rightarrow P(x)], \varnothing\rangle_1, \langle \lambda Q \exists y[paper'(y) \wedge Q(y)], \varnothing\rangle_2\}\rangle$

$\Rightarrow_R \langle \lambda P \forall x[student'(x) \rightarrow P(x)] (\lambda x_1.pres^*(x_2)(x_1)),$
$\{\langle \lambda Q \exists y[paper'(y) \wedge Q(y)], \varnothing\rangle_2\}\rangle$

$\Rightarrow_\beta \langle \forall x[student'(x) \rightarrow pres^*(x_2)(x)], \{\langle \lambda Q \exists y[paper'(y) \wedge Q(y)], \varnothing\rangle_2\}\rangle$

$\Rightarrow_R \langle \lambda Q \exists y[paper'(y) \wedge Q(y)](\lambda x_2.\forall x[student'(x) \rightarrow pres^*(x_2)(x)]), \varnothing\rangle$

$\Rightarrow_\beta \langle \exists y[paper'(y) \wedge \forall x[student'(x) \rightarrow pres^*(y)(x)]], \varnothing\rangle$

## Compositionality

- The Compositionality Principle as stated earlier:
  The meaning of a complex expression is uniquely determined by the meanings of its sub-expressions and its syntactic structure.
- Nested Cooper Storage shows: We can maintain this principle even in the face of semantic (scope) ambiguity
  - as long as we accept that there are multiple meanings
  - the principle is also still true if we see NCS as a nondeterministic process.



## Compositionality and NCS

- Two versions of the Compositionality Principle:
  - on the level of denotations
  - on the level of semantic representations
- Nested Cooper Storage is clearly compositional on the level of semantic representations -- but in a less straightforward way than last week's construction algorithm.
- Compositional on the level of denotations: only in a very indirect sense.

## Other types of scope ambiguities

- Nested Cooper Storage makes the simplifying assumption that only NPs can participate in scope ambiguities.
- This is not true in general:
  - Every student didn't pay attention.
  - Sometimes every student is sleepy.
- NCS can be extended to deal with these, and you'll do it in the exercises, but we'll do something even better next week.



## Scope islands

- Nested Cooper Storage makes the simplifying assumption that NPs can be retrieved at all sentence nodes.
- This is not true in general because sentence-embedding verbs create scope islands:
  - John said that he saw a girl. (2 readings)
  - John said that he saw every girl. (1 reading)
- Universal quantifiers may not cross scope island boundaries; the second sentence doesn't mean "for every girl x, John said that he saw x".

## De dicto/de re ambiguities

- De dicto/de re ambiguities are a special kind of scope ambiguity in which one scope bearer is a verb:

  Helmut Kohl intends to visit a factory.

  $\exists x.factory(x) \wedge intend(hk, \hat{}visit(gs,x))$ (de re)

  $intend(hk, \hat{}\exists x.factory(x) \wedge visit(gs,x))$ (de dicto)
- We need a more expressive (intensional) logic to represent the different readings, but the ambiguity is just a scope ambiguity and can be resolved by NCS.
- Compare the status of "a factory" to the unicorn in "John seeks a unicorn."



## Scope ambiguities in the real world

- Scope ambiguities are not a very intuitive type of ambiguity, and are sometimes not seen as a serious problem for computational linguistics.
- In practice, they are often resolved by context, world knowledge, preferences, etc.
- We consider them here because they pose a fundamental challenge for semantics construction.
- If we want "deep" semantic representations that say something about scope, we must take scope ambiguities into account.

## Scope ambiguities in the real world

- Also, some large-scale grammars (e.g. the English Resource Grammar) compute semantic representations with scope.
- The ERG analyses all NPs as scope bearers to keep the grammar simple. (This is not necessarily correct: proper names, definites, etc.)
- Median number of scope readings in the Rondane corpus: 55.
  (But: The median number of semantic equivalence classes is only 3!)



## Conclusion

- Last week's type-driven semantics construction is a nice first step.
- But it is fundamentally unable to deal with semantically ambiguous sentences.
- Scope ambiguity: Application order of NP representations can be different from syntactic structure.
- Nested Cooper Storage: Equip semantic representations with a quantifier store to allow flexible application of quantifiers; multiple semantic representations per syntactic constituents allowed.