

Preparatory course

Semantics

Stefan Thater
Universität des Saarlandes
16.10.2007

Based on slides by Manfred Pinkal

Units of Language – Subfields of Linguistics

	Grammar	Semantics	Pragmatics
Sound	Phonetics/ Phonology	–	–
Word	Morphology	Lexical Semantics	–
Sentence	Syntax	Compositional Semantics	Pragmatics
Text & Discourse	Text & Discourse Grammar	Discourse Semantics	Pragmatics
	Structure	Meaning	Use

Research Questions in Semantics

1. What is **word meaning**? How can it be appropriately represented and organised? How can it be acquired in an efficient way?
2. What is **sentence meaning** and how can it be appropriately represented? How can it be composed from word meanings and syntactic information?
3. How are semantic **discourse representations** built up from sequences of sentences in text or turns in a dialogue?
4. How does sentence meaning **interact with context**, yielding the intended **utterance information**?
5. How can we **infer the relevant information** in the respective situation from the utterance information?

Representation of Sentence Meaning

1. What is word meaning? How can it be appropriately represented and organised? How can it be acquired in an efficient way?
2. What is sentence meaning and how can it be appropriately represented? How can it be composed from word meanings and syntactic information?
3. How are semantic discourse representations built up from sequences of sentences in text or turns in a dialogue?
4. How does sentence meaning interact with context, yielding the intended utterance information?
5. How can we infer the relevant information in the respective situation from the utterance information?

Representation of Sentence Meaning – Predicate Logic

- *John walks* ⇒ `walk(john)`
- *John likes Mary* ⇒ `like(john, mary)`
- *John is Bill's brother* ⇒ `brother-of(john, bill)`
- *John gives Mary the book* ⇒ `give(john, mary, the-book)`
- *Saarbrücken is closer to France than Hamburg is to Denmark* ⇒ `closer-to(sb, france, hh, denmark)`

Representation of Sentence Meaning – Predicate Logic

- *The big red block is in the box*
⇒ $\text{big}(b) \wedge \text{red}(b) \wedge \text{block}(b) \wedge \text{box}(x) \wedge \text{in}(b, x)$

Predicate Logic: Syntax

- Non-logical expressions:
 - Individual constants: CON
 - n-place predicate symbols: REL^n ($n \geq 0$)
- Individual variables: VAR
- Terms: $TERM = VAR \cup CON$
- Atomic formulas:
 - $R(t_1, \dots, t_n)$ for $R \in REL^n, t_1, \dots, t_n \in TERM$
 - $s = t$ for $s, t \in TERM$

Predicate Logic: Syntax

- The set of well-formed formulae of predicate logic is the smallest set FORM such that
 - all atomic formulas are in FORM
 - if A, B are in FORM, then $\neg A$, $(A \wedge B)$, $(A \vee B)$, $(A \rightarrow B)$, $(A \leftrightarrow B)$ are in FORM
 - If x is an individual variable and A is in FORM, then $\forall xA$ and $\exists xA$ are in FORM

Predicate Logic: Semantics

- **Model structures** $M = \langle U, V \rangle$
 - U (or U_M) is a non-empty universe (domain of individuals)
 - V (or V_M) is an interpretation function, which assigns individuals ($\in U_M$) to individual constants and n -ary relations between individuals ($\in U_M^n$) to n -place predicate symbols.
- **Assignment function** for variables $g: \text{VAR} \rightarrow U_M$

Predicate Logic: Semantics

- Interpretation of terms with respect to a model structure M and a variable assignment g :
 - $\llbracket \alpha \rrbracket^{M,g} = V_M(\alpha)$, if α is an individual constant
 - $\llbracket \alpha \rrbracket^{M,g} = g(\alpha)$, if α is a variable

Predicate Logic: Semantics

- Interpretation of formulas with respect to a model structure M and variable assignment g :

$$\llbracket R(t_1, \dots, t_n) \rrbracket^{M,g} = 1 \text{ iff } (\llbracket t_1 \rrbracket^{M,g}, \dots, \llbracket t_n \rrbracket^{M,g}) \in V_M(R)$$

$$\llbracket s = t \rrbracket^{M,g} = 1 \text{ iff } \llbracket s \rrbracket^{M,g} = \llbracket t \rrbracket^{M,g}$$

$$\llbracket \neg\phi \rrbracket^{M,g} = 1 \text{ iff } \llbracket \phi \rrbracket^{M,g} = 0$$

$$\llbracket \phi \wedge \psi \rrbracket^{M,g} = 1 \text{ iff } \llbracket \phi \rrbracket^{M,g} = 1 \text{ and } \llbracket \psi \rrbracket^{M,g} = 1$$

$$\llbracket \phi \vee \psi \rrbracket^{M,g} = 1 \text{ iff } \llbracket \phi \rrbracket^{M,g} = 1 \text{ or } \llbracket \psi \rrbracket^{M,g} = 1$$

$$\llbracket \phi \rightarrow \psi \rrbracket^{M,g} = 1 \text{ iff } \llbracket \phi \rrbracket^{M,g} = 0 \text{ or } \llbracket \psi \rrbracket^{M,g} = 1$$

$$\llbracket \phi \leftrightarrow \psi \rrbracket^{M,g} = 1 \text{ iff } \llbracket \phi \rrbracket^{M,g} = \llbracket \psi \rrbracket^{M,g}$$

$$\llbracket \exists x\phi \rrbracket^{M,g} = 1 \text{ iff there is } a \in U_M \text{ such that } \llbracket \phi \rrbracket^{M,g[x/a]} = 1$$

$$\llbracket \forall x\phi \rrbracket^{M,g} = 1 \text{ iff for all } a \in U_M, \llbracket \phi \rrbracket^{M,g[x/a]} = 1$$

- $g[x/a]$ is the variable assignment which is identical to g except that it assigns the individual a to the variable x .

Predicate Logic: Semantics

- Formula A is **true in the model structure M** iff $\llbracket A \rrbracket^{M,g} = 1$ for every variable assignment g .
- A model structure M **satisfies** (or: is a model for) a set of formulas Γ iff every formula $A \in \Gamma$ is true in M .
- A set of formulas Γ **entails** formula A (notation: $\Gamma \models A$) iff A is true in every model of Γ .

Talking about Dolphins



Talking about Dolphins

- *Dolphins are mammals, not fish.*
 - $\forall d (\text{dolphin}(d) \rightarrow \text{mammal}(d) \wedge \neg \text{fish}(d))$
- *Dolphins live in pods.*
 - $\forall d (\text{dolphin}(d) \rightarrow \exists x (\text{pod}(p) \wedge \text{live-in}(d,p)))$
- *Dolphins give birth to one baby at a time.*
 - $\forall d (\text{dolphin}(d) \rightarrow$
 $\quad \forall x \forall y \forall t (\text{give-birth-to}(d,x,t) \wedge \text{give-birth-to}(d,y,t) \rightarrow x=y)$

Semantics and Inference

1. What is word meaning? How can it be appropriately represented and organised? How can it be acquired in an efficient way?
2. How can sentence meaning be appropriately represented? How can it be composed from word meanings and syntactic information?
3. How are semantic discourse representations built up from sequences of sentences in text or turns in a dialogue?
4. How does sentence meaning interact with context, yielding the intended utterance information?
5. How can we infer the relevant information in the respective situation from the utterance information?

Entailment and Deduction

- Calculi can be implemented to obtain:
 - **theorem provers**: check entailment, validity, and unsatisfiability
 - **model builders**: check satisfiability, compute models
 - **model checkers**: determine whether model satisfies formula

Inference in Natural Language Understanding: Examples

- *Have you ever been in France?*
I was in Paris last year.
- *Does Bill like lamb chops?*
Bill is a vegetarian.
- *Which Airlines buy planes from Airbus?*
Airbus sells five A380 planes to China Southern.

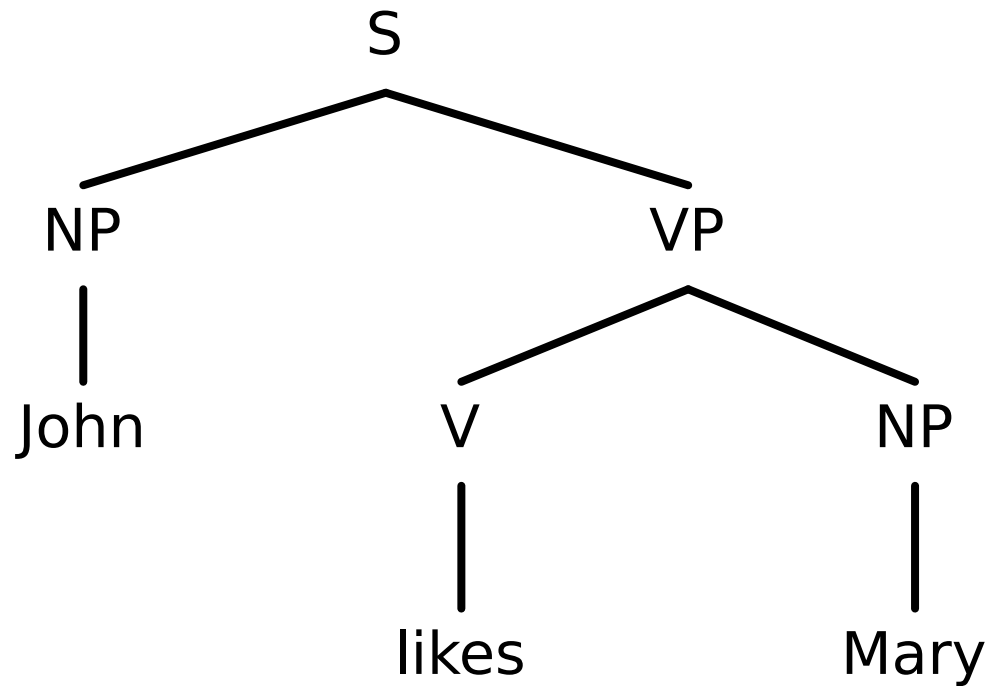
Logic as a Framework for Natural Language Semantics

- Logic supports precise, consistent and controlled meaning representation via truth-conditional interpretation.
- (First-order) Logic provides deduction systems to model inference processes, controlled through a formal entailment concept.
- Suggested Reading: L.T.F. Gamut, *Logic, Language, and Meaning*. Volume1: Introduction to Logic. University of Chicago Press 1991

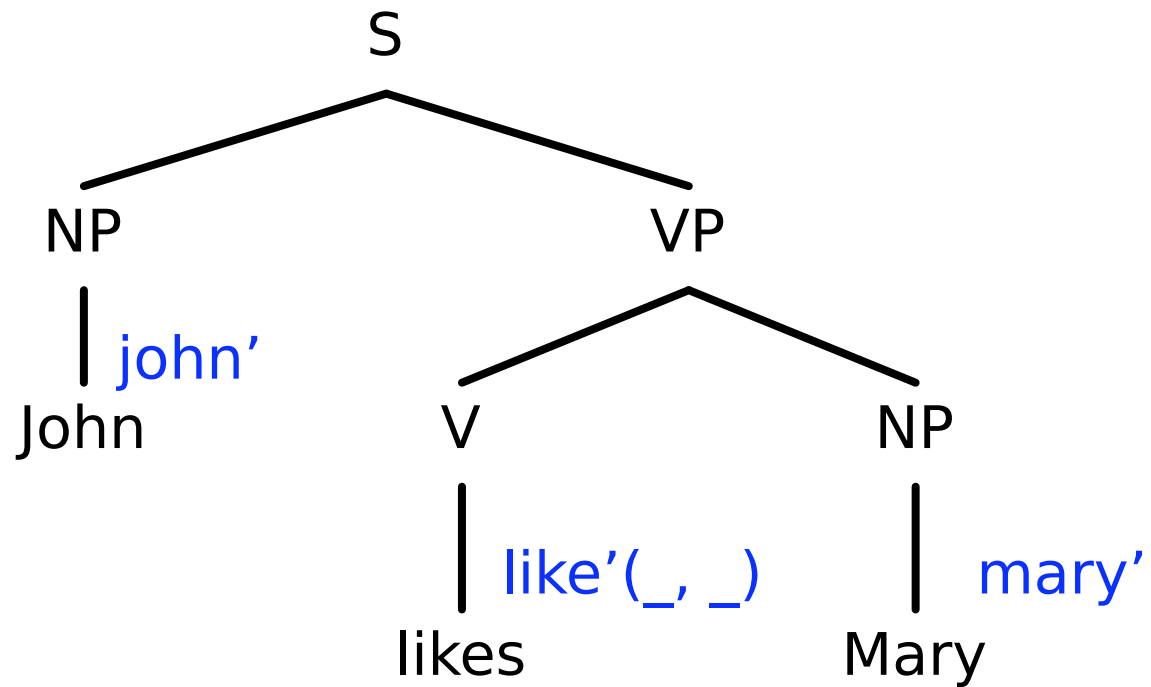
Construction of Sentence Meaning [1]

1. What is word meaning? How can it be appropriately represented and organised? How can it be acquired in an efficient way?
2. How can sentence meaning be appropriately represented?
How can it be composed from word meanings and syntactic information?
3. How are semantic discourse representations built up from sequences of sentences in text or turns in a dialogue?
4. How does sentence meaning interact with context, yielding the intended utterance information?
5. How can we infer the relevant information in the respective situation from the utterance information?

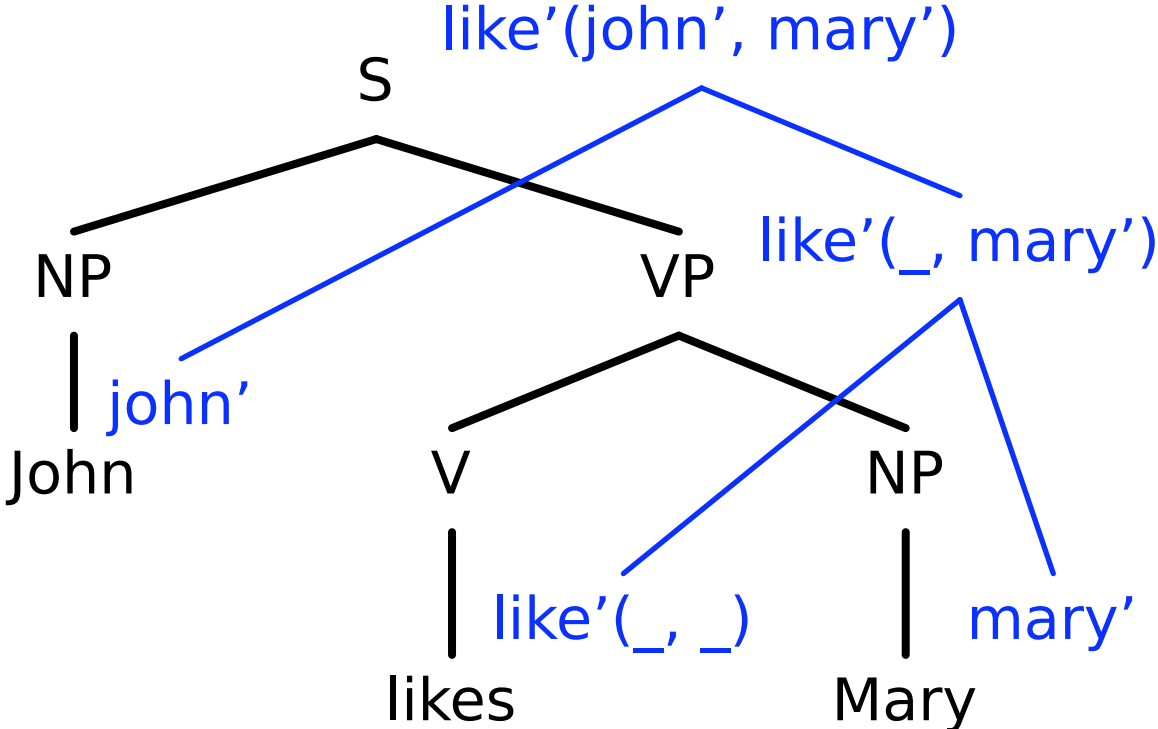
Basic Semantic Composition



Basic Semantic Composition

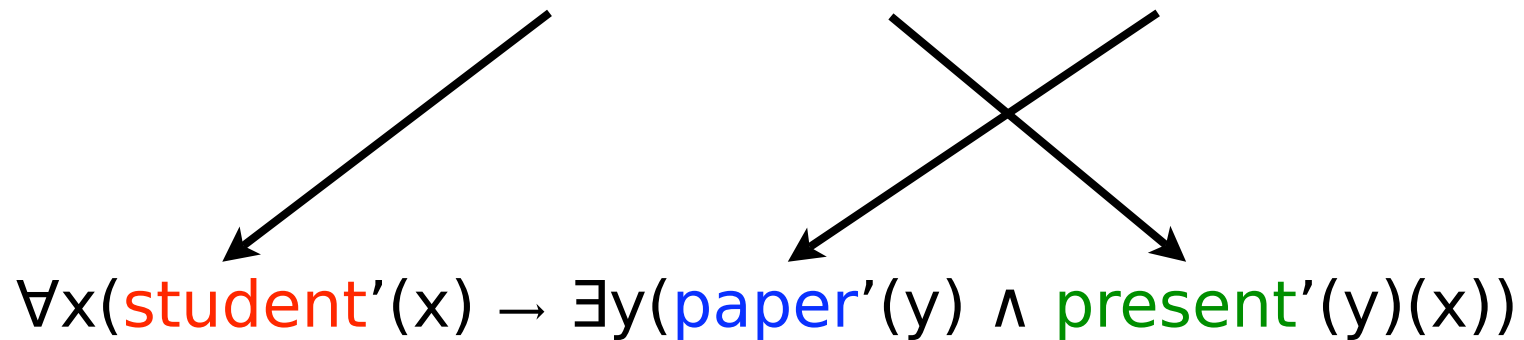


Basic Semantic Composition

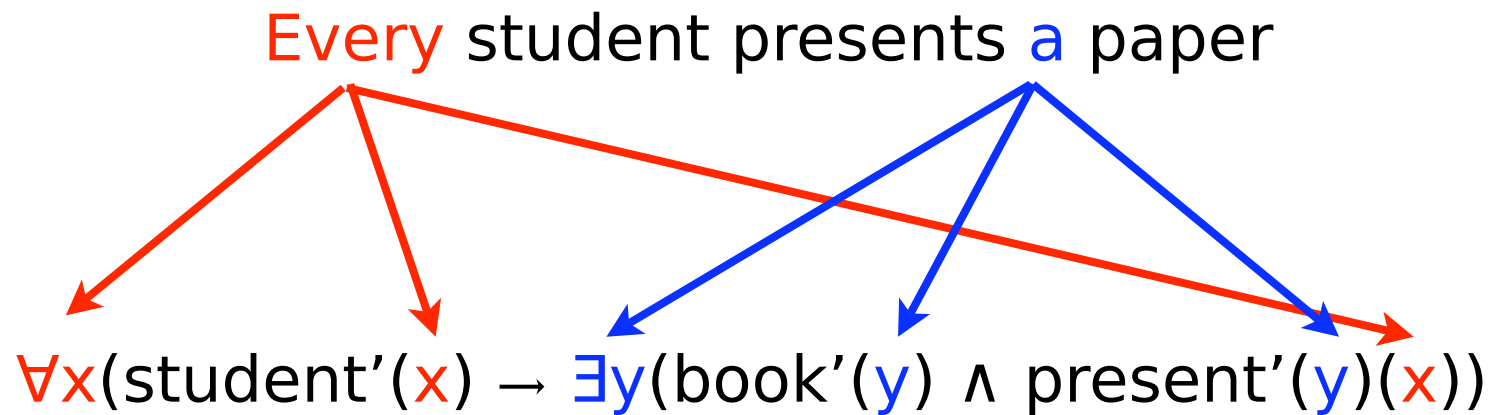


A Challenge for Semantic Composition

Every student presents a paper



A Challenge for Semantic Composition



Word Meaning

1. What is word meaning? How can it be appropriately represented and organised? How can it be acquired in an efficient way?
2. How can sentence meaning be appropriately represented? How can it be composed from word meanings and syntactic information?
3. How are semantic discourse representations built up from sequences of sentences in text or turns in a dialogue?
4. How does sentence meaning interact with context, yielding the intended utterance information?
5. How can we infer the relevant information in the respective situation from the utterance information?

Talking (again) about Dolphins



Sentence Semantics (Predicate Logic)

Dolphins **are** mammals, **not** fish. **They are** warm blooded **like** man, **and** give birth to **one** baby called **a** calf at **a** time. At birth **a** bottlenose dolphin calf **is about** 90-130 cms long **and will** grow to **approx.** 4 metres, living up to 40 years. **They are** highly sociable animals, living in pods **which are fairly** fluid, with dolphins from **other** pods interacting with **each other** from time to time.

Lexical Semantics

Dolphins are mammals, not fish. They are warm blooded like man, and give birth to one baby called a calf at a time. At birth a bottlenose dolphin calf is about 90-130 cms long and will grow to approx. 4 metres, living up to 40 years. They are highly sociable animals, living in pods which are fairly fluid, with dolphins from other pods interacting with each other from time to time.

Challenges in Lexical Semantics

- Provision of lexical-semantic information is highly labor- and cost-intensive because the lexicon is
 - very large
 - undelimitable
 - heterogeneous
 - subject to application-dependent variation

Challenges in Lexical Semantics

- Single words can be multiply ambiguous
- There is no clear boundary for the set of readings of a lexical item, because of meaning extensions and figurative uses (metaphor, metonymy):
 - to like Shakespeare
 - to eat / wear rabbit
 - to grasp an idea

Challenges in Lexical Semantics

- The concepts corresponding to single readings of a word are typically multi-layered, consisting of heterogeneous kinds of information:
 - “Propositional” layer – can be paraphrased in language, symbolically represented in a logical framework
 - Layer of visual (or other sensory) prototypes
 - Stereotypical information
- No sharp boundary between word meaning and extra-linguistic knowledge (“world-knowledge”)

Semantic Relations

- Hyponymy/Hypernymy (the “IS-A relation): dolphin – mammal
- Synonymy: case – bag
- Meronymy/Holonymy
 - Part/Whole : branch – tree
 - Member/Group: tree – forest
 - Matter/Object: wood – tree
- Contrast
 - Complementarity: boy – girl
 - Antonymy: long – short

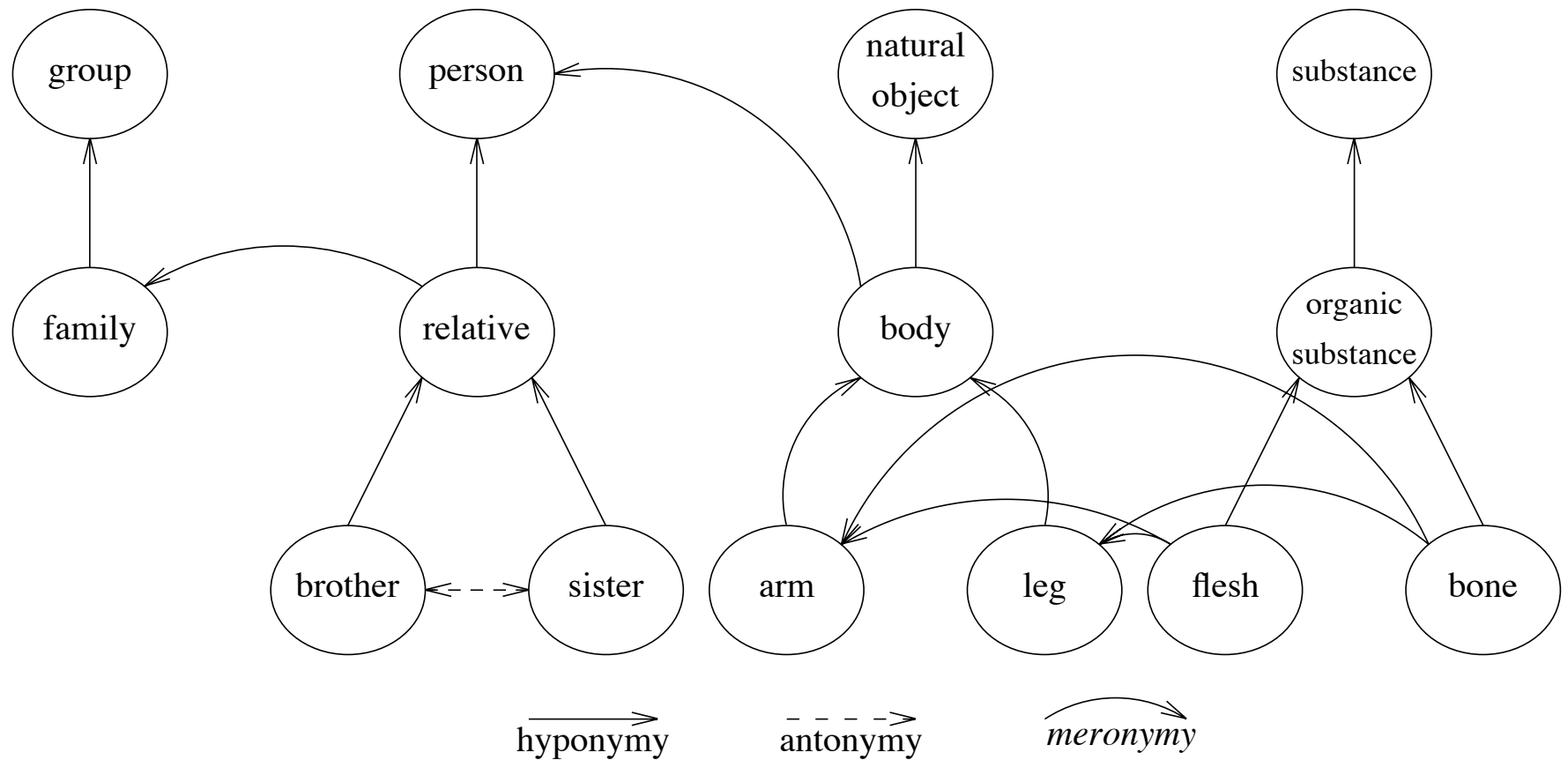
WordNet

- WordNet is a large lexical-semantic resource, organised as a semantic network.
- Concepts / readings in WordNet are represented by so-called “synsets” – sets of synonymous words. These “synsets” are the nodes of the semantic network.
- WordNet consists of different, basically unrelated databases for common nouns, verbs, adjectives (and adverbs)
- The respective hierarchies have a number of “unique beginners” each.

An Example: “case”

- {case, carton}
- {case, bag, suitcase}
- {case, pillowcase, slip}
- {case, cabinet, console}
- {case, casing (the enclosing frame around a door or window opening)}
- {case (a small portable metal container)}

A Fragment of the WordNet Noun Network



WordNet

- English WordNet: about 150.000 lexical items
 - Web Interface: <http://wordnet.princeton.edu/perl/webwn>
 - General Info: <http://wordnet.princeton.edu/>
- GermaNet: a German WordNet version with about 90.000 lexical items
- Versions of WordNet for available for about 30 languages

Thematic Roles and Frames

- *Which Airlines buy planes from Airbus?*
- Airbus sells five A380 superjumbo planes to China Southern for 220 million Euro
- China Southern buys five A380 superjumbo planes from Airbus for 220 million Euro
- Airbus arranged with China Southern for the sale of five A380 superjumbo planes at a price of 220 million Euro
- Five A380 superjumbo planes will go for 220 million Euro to China Southern

Thematic Roles and Frames

- COMMERCIAL TRANSACTION
 - **SELLER:** Airbus
 - **BUYER:** China Southern
 - **GOODS:** five A380 superjumbo planes
 - **PRICE:** 220 million Euro

Berkeley FrameNet

- Frames: an inventory of conceptual structures modelling a prototypical situation like “COMMERCIAL TRANSACTION”
- Semantic roles are locally valid only and accordingly called “Frame Elements” (FE):
 - FEs of the COMMERCIAL TRANSACTION frame: BUYER, SELLER, GOODS, PRICE, ...
- A set of “target words” associated with each frame: e.g., for COMMERCIAL TRANSACTION:
 - buy, sell, pay, spend, cost, charge,
 - price, change, debt, credit, merchant, broker, shop
 - tip, fee, honorarium, tuition

Discourse Semantics

1. What is word meaning? How can it be appropriately represented and organised? How can it be acquired in an efficient way?
2. What is sentence meaning and how can it be appropriately represented? How can it be composed from word meanings and syntactic information?
3. How are semantic discourse representations built up from sequences of sentences in text or turns in a dialogue?
4. How does sentence meaning interact with context, yielding the intended utterance information?
5. How can we infer the relevant information in the respective situation from the utterance information?

Semantic Context Dependence

- Deictic expressions point to objects in the physical / visual utterance situation:
 - *I, you, here, this, ...*
- Anaphoric expressions refer to objects in the linguistic context
 - *he, she, it, his, her, one (“the one you are holding”)*

Semantic Context Dependence

- Almost all expressions are dependent on context in one or the other way.
 - *Every student* must be familiar with the basic properties of first-order logic.
 - John *always* is late.
 - Its hot and sunny *everywhere*.
 - Dolphins from different pods interact from *time to time*.
 - *Another one, please!*

Definite and Indefinite Noun Phrases

- In text and discourse semantics, there is a “collaboration” between definite and indefinite noun phrases.
 - *A professor owns a book. He likes the book.*
- Indefinite noun phrases introduce reference objects (“discourse referents”). Definite noun phrases can be used to refer to them anaphorically.
- Discourse representation theory (DRT) models this process.

DRT: An example

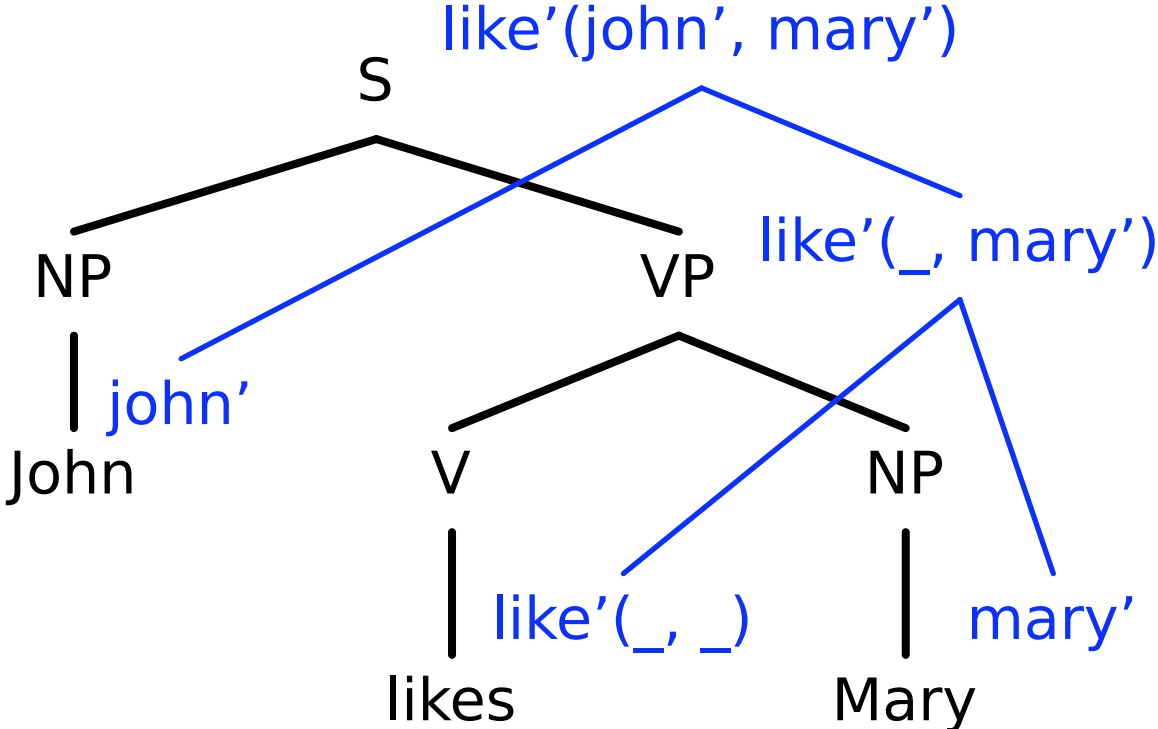
- A professor owns a book. He likes the book.

x y z u
professor(x) book(y) own(x, y) z = x u = y like(z, u)

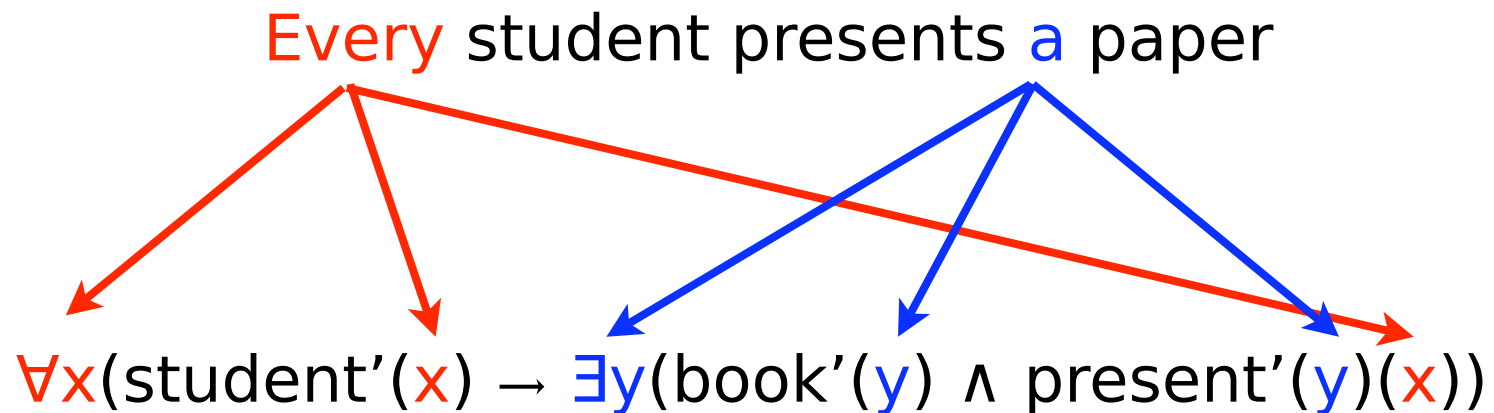
Construction of Sentence Meaning [2]

1. What is word meaning? How can it be appropriately represented and organised? How can it be acquired in an efficient way?
2. What is sentence meaning and how can it be appropriately represented? **How can it be composed from word meanings and syntactic information?**
3. How are semantic discourse representations built up from sequences of sentences in text or turns in a dialogue?
4. How does sentence meaning interact with context, yielding the intended utterance information?
5. How can we infer the relevant information in the respective situation from the utterance information?

Basic Semantic Composition



A Challenge for Semantic Composition



Do we need more than First-order Logic?

- *(This is) a big red block*
 - $\text{big}(b) \wedge \text{red}(b) \wedge \text{block}(b)$
- *John is a blond criminal*
 - $\text{criminal}(j) \wedge \text{blond}(j)$
- *John is good piano player*
 - $\text{piano-player}(j) \wedge \text{good}(j)$?
- *John is an alleged criminal*
 - $\text{criminal}(j) \wedge \text{alleged}(j)$???

Do we need more than First-order Logic?

- *Bill has the same hair colour as John.*
- *Santa Claus has all the attributes of a sadist.*

Type Theory

- The set of **basic types** is $\{e, t\}$:
 - e (for entity) is the type of individual terms
 - t (for truth value) is the type of formulas
- All pairs $\langle \sigma, \tau \rangle$ made up of (basic or complex) types σ, τ are types. $\langle \sigma, \tau \rangle$ is the type of functions which map arguments of type σ to values of type τ .
- In short: The set of types is the smallest set T such that $e, t \in T$, and if $\sigma, \tau \in T$, then also $\langle \sigma, \tau \rangle \in T$.

Some Complex Types for Natural Language Semantics

- Individuals: e
- Sentences: t
- One-place predicate constants: $\langle e, t \rangle$
- Two-place relations: $\langle e, \langle e, t \rangle \rangle$
- Sentence adverbials: $\langle t, t \rangle$
- Attributive adjectives: $\langle \langle e, t \rangle, \langle e, t \rangle \rangle$
- Degree modifiers: $\langle \langle \langle e, t \rangle, \langle e, t \rangle \rangle, \langle \langle e, t \rangle, \langle e, t \rangle \rangle \rangle$

The Inventory of Type Theory

- Constants (CON_τ) and variables (VAR_τ) of every type τ
- The usual predicate logic operators

Type-theoretic syntax [2]

- The sets of well-formed expressions WE_τ for every type τ are given by:
 - $CON_\tau \subseteq WE_\tau$ for every type τ
 - If $\alpha \in WE_{\langle\sigma, \tau\rangle}$, $\beta \in WE_\sigma$, then $\alpha(\beta) \in WE_\tau$.
 - If A, B are in WE_t , then so are $\neg A$, $(A \wedge B)$, $(A \vee B)$, $(A \rightarrow B)$, $(A \leftrightarrow B)$
 - If A is in WE_t , then so are $\forall vA$ and $\exists vA$, where v is a variable of arbitrary type.
 - If α, β are well-formed expressions of the same type, then $\alpha = \beta \in WE_t$.
 - If α is in WE_τ and v is a variable of type σ , then $\lambda v\alpha$ is a well-formed expression of type $\langle\sigma, \tau\rangle$.

Building Well-Formed Expressions

- *Bill drives fast.*

$$\frac{\frac{\text{drive: } \langle e, t \rangle \quad \text{fast: } \langle \langle e, t \rangle, \langle e, t \rangle \rangle}{\text{bill: } e \quad \text{fast(drive): } \langle e, t \rangle}}{\text{fast(drive)(bill): } t}$$

- *Mary works in Saarbrücken*

$$\frac{\frac{\text{mary: } e \quad \text{work: } \langle e, t \rangle}{\text{work(mary): } t} \quad \frac{\text{in: } \langle e, \langle t, t \rangle \rangle \quad \text{sb: } e}{\text{in(sb): } \langle t, t \rangle}}{\text{in(sb)(work(mary))): } t}$$

Type-Theoretic Semantics

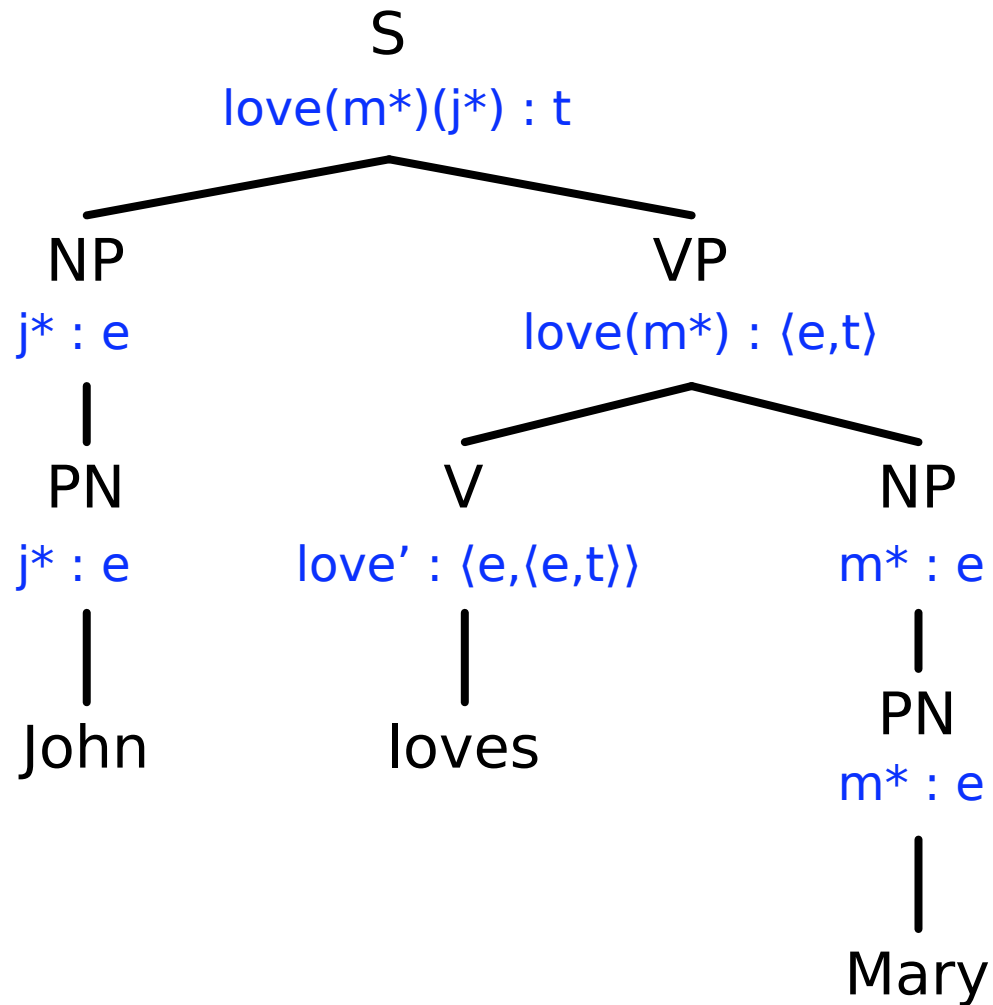
- The semantics of type theory is completely parallel to its syntax:
 - Expressions of type e denote entities.
 - Expressions of type t denote truth values
 - Expression of type $\langle \sigma, \tau \rangle$ denote functions from denotations of type σ to denotations of type τ .

Frege's Principle

... or the Principle of Compositionality:

The meaning of a complex expression is uniquely determined by the meanings of its (immediate) sub-expressions and its syntactic structure.

An Example



λ -Abstraction

- $\lambda x(\text{drive}(x) \wedge \text{drink}(x))$
 - a term of type $\langle e, t \rangle$
 - denotes the property of being “an x such that x drives and drinks”
- λ -abstraction is an operation that takes an expression and “opens” or “re-opens” specific argument positions by abstracting over a variable
- The result of abstraction over individual variable x in the formula ‘ $\text{drive}(x) \wedge \text{drink}(x)$ ’ results in the complex predicate ‘ $\lambda x(\text{drive}(x) \wedge \text{drink}(x)).$ ’

“John drinks and drives”

$$\frac{\frac{\text{drive}' : \langle e,t \rangle \quad x : e}{\text{drive}'(x) : t}}{\frac{\frac{\text{drink}' : \langle e,t \rangle \quad x : e}{\text{drink}'(x) : t}}{\text{drive}'(x) \wedge \text{drink}'(x) : t}} \quad \text{john} : e$$
$$\frac{\lambda x(\text{drive}'(x) \wedge \text{drink}'(x)) : \langle e,t \rangle \quad \text{john} : e}{\lambda x(\text{drive}'(x) \wedge \text{drink}'(x))(\text{john}) : t}$$

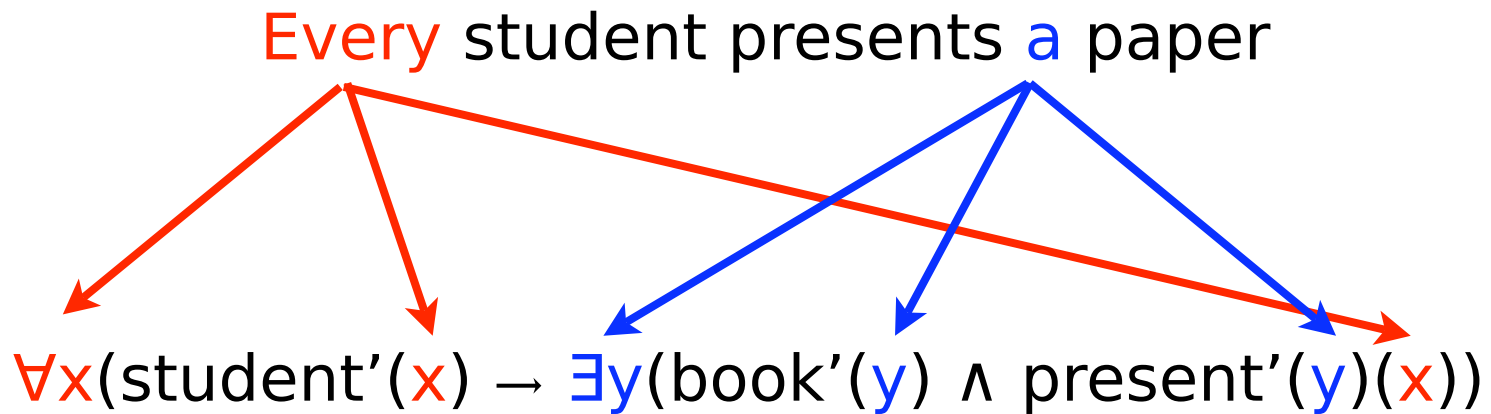
β -Reduction

- $\lambda v \alpha(\beta) \Leftrightarrow [\beta/v]\alpha$, if all free variables in β are free for v in α
- $[\beta/v]\alpha$ denotes the result of substituting all free occurrences of v by β in α .
- Informally, “free for x ” means that free occurrences of variables in β remain free in $[\beta/v]\alpha$

“John drinks and drives”

- $\lambda x(\text{drive}'(x) \wedge \text{drink}'(x))(\text{john})$
 $\Rightarrow_{\beta} \text{drive}'(\text{john}) \wedge \text{drink}'(\text{john})$

Back to the Composition Problem



A Unified Semantics of Noun Phrases

- *John works.*

$$\frac{j^* : e \quad \text{work}' : \langle e, t \rangle}{\text{work}'(j^*) : t}$$

- *Every student works.*

$$\frac{\text{every-student}' : e \quad \text{work}' : \langle e, t \rangle}{\text{work}'(\text{every-student}') : t}$$

- **But this does not really work!**
- (what is the denotation of “every-student’”?)

A Unified Semantics of Noun Phrases

- So let's try it the other way round:

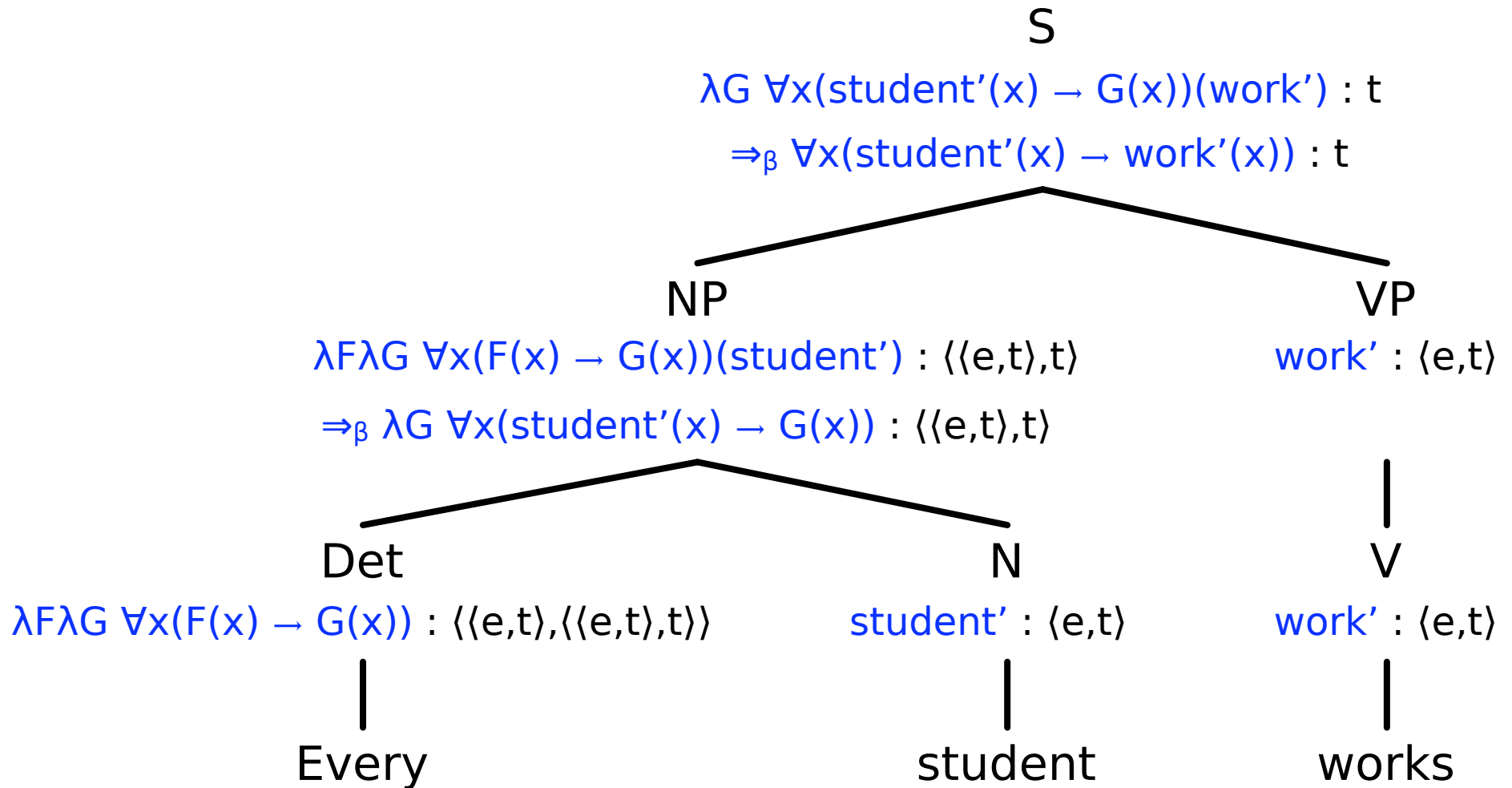
$$\frac{\text{every-student}' : \langle \langle e,t \rangle, t \rangle \quad \text{work}' : \langle e,t \rangle}{\text{every-student}'(\text{work}') : t}$$

- 'Every student' is a complex second-order predicate that is true of a first-order predicate, if all students are in the denotation of that predicate.

Noun Phrases as λ -Expressions

- 'Every student' is a complex second-order predicate that is true of a first-order predicate, if all students are in the denotation of that predicate.
- This semantic information can be straightforwardly encoded as a lambda term:
 - $\lambda G \forall x(\text{student}(x) \rightarrow G(x))$
- Accordingly, the determiner every can be represented as:
 - $\lambda F \lambda G \forall x(F(x) \rightarrow G(x))$

“Every student works.”



Recommended Reading

- Textbook: L.T.F. Gamut, Logic, Language, and Meaning. Volume 2: Intensional Logic and Logical Grammar. University of Chicago Press 1991