Preparatory Course

Semantic Theory

Stefan Thater

Universität des Saarlandes

2008-10-14

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

- What is word meaning? How can it be represented and organised? How can it be acquired efficiently?
- What is sentence meaning and how can it be represented? How can it be composed from word meanings and syntactic information?
- How are semantic discourse representations built up from sequences of sentences?
- How does sentence meaning interact with context, yielding the intended utterance information?
- How can we infer the relevant information in the respective situation from the utterance information?

Research Questions in Semantics

- What is word meaning? How can it be represented and organised? How can it be acquired efficiently?
- What is sentence meaning and how can it be represented? How can it be composed from word meanings and syntactic information?
- How are semantic discourse representations built up from sequences of sentences?
- How does sentence meaning interact with context, yielding the intended utterance information?
- How can we infer the relevant information in the respective situation from the utterance information?

Dolphins

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.

Major Word-Semantic Categories

- Function words:
  - Connectives and quantifiers
  - Auxiliary and modal verbs
  - Temporal and modal adverbials
  - Anaphoric pronouns, articles, …
- Content words
  - Common nouns
  - Full verbs
  - Adjectives
- Other: Named Entities, Numbers, …

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 bottle-nose dolphin calf is about 90-130 cms long and will grow to approx. 4 meters, 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.

Common Nouns + Adjectives + Verbs

The Word-Meaning Relation

- No one-to-one relation between:
  - phonological/orthographic words and
  - senses (word meanings, concepts)
- Synomymy: One sense/concept can be encoded in different words (e.g., *car* and *automobile*).
- Lexical ambiguity: One word can be associated with several senses.

Lexical Ambiguity

(1) a. The bank of the river

b. The richest bank in the city

(2) a. The bank raised interest rates yesterday.

b. The store is next to the new bank.

Lexical Ambiguity

- Homonymy: Ambiguity between unrelated senses
  - bank: river bank or financial institution
- Polysemy: Ambiguity between semantically related concepts
- Unsystematic cases of polysemy:
  - bank: financial institution - blood bank
  - case: carton, suitcase, pillowcase
- Systematic polysemy
  - rabbit, dear, chicken: animal – meat
  - fast: fast car, fast road, fast driver

Representing Meaning

- Monolingual dictionaries, alphabetically ordered lemmas with enumeration and informal descriptions of readings
  - Oxford English Dictionary
  - Webster‘s
  - Wahrig
  - Duden
  - …

Representing Meaning

- A thesaurus presents the lexicon of a language in a hierarchical ordering:
  - Roget‘s Thesaurus (English, since 1805)
  - Dornseiff‘s “Deutscher Wortschatz nach Sachgruppen” (German, 1910)
- Thesauri provide information about the basic semantic relation of Hyponymy (“IS-A“ relation)

http://wordnet.princeton.edu

Representing Meaning

- WordNet is a large hierarchical lexical-semantic resource providing meaning representations in terms of relations between concepts in a systematic way.
- Words – Concepts:
  - The same word can express different concepts (ambiguity)
  - The same concept can be expressed by different words (synonymy).
- WordNet: concepts are represented by "synsets:" sets of synonymous words. Synsets are the basic units of WordNet.

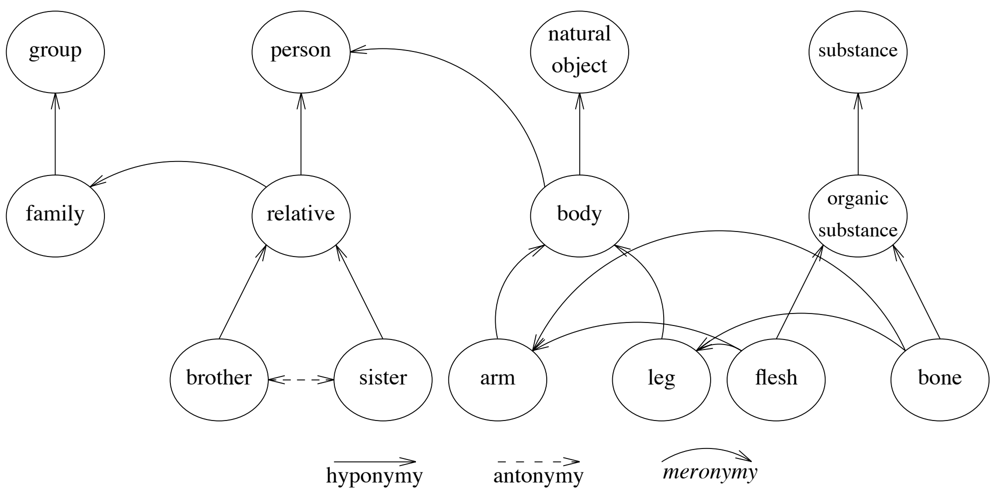
Some Synsets for "case"

- {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)}

Semantic Relations

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

A Fragment of the WordNet Noun Network



The Layer of Predicate-Argument Relations

- (Almost) Equivalent sentences with different realizations of “the same” semantic argument positions:
  - *Mary likes John*
  - *John pleases Mary*

  - *Mary gave Peter the book.*
  - *Peter received the book from Mary.*

Thematic Roles (Fillmore 1968)

- Thematic roles describe the conceptual participants in a situation in a generic way, independent from their grammatical realization.

Thematic Roles:
A Textbook Example

- *John gave Mary the book.*
- *Mary received the book from John.*

- *[$_{Subj}$ John] gave [$_{DObj}$ Mary] [$_{AObj}$ the book].*
- *[$_{Subj}$ Mary] received [$_{DObj}$ the book] [$_{PObj}$ from John].*

- *John gave Mary the book.*
- *Mary received the book from John.*

Thematic Roles:
A Textbook Example

- *give:* Subj ⇔ Agent
  AObj ⇔ Theme
  DObj ⇔ Recipient

- *receive:* Subj ⇔ Recipient
  AObj ⇔ Theme
  PObj from ⇔ Agent

Thematic Roles:
A Textbook Example

- *[$_{Subj}$ John] gave [$_{DObj}$ Mary] [$_{AObj}$ the book].*
- *[$_{agt}$ John] gave [$_{rec}$ Mary] [$_{pat}$ the book].*

- *[$_{Subj}$ Mary] received [$_{DObj}$ the book] [$_{PObj}$ from John].*
- *[$_{rec}$ Mary] received [$_{pat}$ the book] [$_{ag}$ from John].*

Thematic Roles:
A Textbook Example

- give(agt: John, pat: the book, rec: Mary)
- receive(agt: John, pat: the book, rec: Mary)

- **TRANSACTION**(agt: John, pat: the book, rec: Mary)

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

The Berkeley FrameNet Database

- A lexicon with thematic role information for verbs and other relational expressions. Basic unit: frames.
- Frames (like "comercial transaction") provide:
  - Role information
  - Grammatical realization patterns (role linking)
  - Annotations of example sentences (from BNC)
- Current release: about 700 frames and 8000 lexical units (mostly verbs). Planned: 15.000 verb descriptions.

http://framenet.icsi.berkeley.edu

Research Questions in Semantics

- What is word meaning? How can it be represented and organised? How can it be acquired efficiently?
- What is sentence meaning and how can it be represented? How can it be composed from word meanings and syntactic information?
- How are semantic discourse representations built up from sequences of sentences?
- How does sentence meaning interact with context, yielding the intended utterance information?
- How can we infer the relevant information in the respective situation from the utterance information?

What is Sentence Meaning?

- Basic assumption: the core meaning of a natural language sentence is given by its truth-conditions.
  - to know the meaning of a sentence is to know under which conditions the sentence is true.
- „John likes Mary“
  - ⟦John likes Mary⟧ = 1 iff John likes Mary

Logic and Formal Semantics

- In formal (and computational) semantics, logical expressions are used to represent meanings of natural language expressions.
  - Logic supports precise and unambiguous meaning representation via truth-conditional interpretation.
  - Logic provides deduction systems to model inference processes, controlled through a formal entailment concept.
  - Logic supports uniform modelling of the semantic

Representing 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)

Representing Sentence Meaning – Predicate Logic

(1) *A rabbit is in a hat*

$\Rightarrow \exists x(\text{rabbit}(x) \wedge \exists y(\text{hat}(y) \wedge \text{in}(x, y)))$

(2) *A white rabbit is in a hat*

$\Rightarrow \exists x(\text{rabbit}(x) \wedge \text{white}(x) \wedge \exists y(\text{hat}(y) \wedge \text{in}(x, y)))$

Predicate Logic – Vocabulary

- Non-logical symbols:
  - Individual constants: CON
  - n-place predicate symbols: REL^n ($n \geq 0$)
- Individual variables: VAR
- Logical symbols: $\wedge$, $\vee$, $\neg$, $\rightarrow$, $\leftrightarrow$, $\forall$, $\exists$,),(

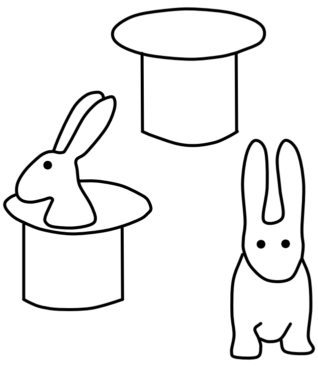
Predicate Logic – Syntax

- Terms: TERM = VAR $\cup$ CON
- Atomic formulas:
  - $R(t_1, \ldots, t_n)$ for $R \in REL^n$, $t_1, \ldots, t_n \in$ TERM
  - $s = t$ for $s, t \in$ TERM
- 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 = ⟨U_M, V_M⟩
  - U_M is a non-empty universe (domain of individuals)
  - V_M is an interpretation function, which assigns individuals (∈ U_M) to individual constants and n-ary relations between individuals (∈ U_M^n) to n-place predicate symbols.
- Assignment function for variables g: VAR → U_M

A Simple Example



$$M = \langle U_M, V_M \rangle$$
$$U_M = \{ r_1, r_2, h_1, h_2 \}$$
$$V_M(\text{rabbit}) = \{ r_1, r_2 \}$$
$$V_M(\text{white}) = \{ r_2 \}$$
$$V_M(\text{hat}) = \{ h_1, h_2 \}$$
$$V_M(\text{in}) = \{ (r_1, h_1) \}$$

Predicate Logic: Semantics

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

Predicate Logic: Semantics

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

$[\![R(t_1, \ldots, t_n)]\!]^{M,g} = 1$ iff $([\![t_1]\!]^{M,g}, \ldots, [\![t_n]\!]^{M,g}) \in V_M(R)$

$[\![s = t]\!]^{M,g} = 1$ iff $[\![s]\!]^{M,g} = [\![t]\!]^{M,g}$

$[\![\neg\varphi]\!]^{M,g} = 1$ iff $[\![\varphi]\!]^{M,g} = 0$

$[\![\varphi \wedge \psi]\!]^{M,g} = 1$ iff $[\![\varphi]\!]^{M,g} = 1$ and $[\![\psi]\!]^{M,g} = 1$

$[\![\varphi \vee \psi]\!]^{M,g} = 1$ iff $[\![\varphi]\!]^{M,g} = 1$ or $[\![\psi]\!]^{M,g} = 1$

$[\![\varphi \rightarrow \psi]\!]^{M,g} = 1$ iff $[\![\varphi]\!]^{M,g} = 0$ or $[\![\psi]\!]^{M,g} = 1$

$[\![\varphi \leftrightarrow \psi]\!]^{M,g} = 1$ iff $[\![\varphi]\!]^{M,g} = [\![\psi]\!]^{M,g}$

$[\![\exists x\varphi]\!]^{M,g} = 1$ iff there is $a \in U_M$ such that $[\![\varphi]\!]^{M,g[x/a]} = 1$

$[\![\forall x\varphi]\!]^{M,g} = 1$ iff for all $a \in U_M$, $[\![\varphi]\!]^{M,g[x/a]} = 1$

- 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

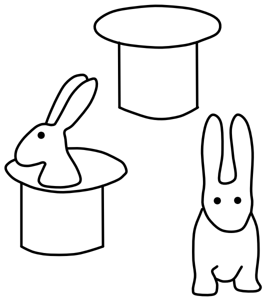
- Formula A is true in a model structure M iff $[[A]]^{M,g} = 1$ for every variable assignment g.
- A model structure M satisfies (is a model for) a set of formulas Γ iff every formula A ∈ Γ is true in M.
- A set of formulas Γ entails formula A (Γ ⊨ A) iff A is true in every model of Γ.

Rabbits

- *A rabbit is in a hat*
- ∃x(rabbit(x) ∧ ∃y(hat(y) ∧ in(x, y)))
- $[[\exists x(\text{rabbit}(x) \land \exists y(\text{hat}(y) \land \text{in}(x, y)))]]^{M,g} = 1$
  - iff there is a ∈ U_M such that $[[\text{rabbit}(x) \land \ldots]]^{M,g[x/a]} = 1$
  - iff there is a ∈ U_M such that $[[\text{rabbit}(x)]]^{M,g[x/a]} = 1$ and $[[\exists y(\text{hat}(y) \land \text{in}(x, y))]]^{M,g[x/a]} = 1$
  - […]
  - iff there is a ∈ U_M such that a ∈ V_M(rabbit) and there is b ∈ U_M such that b ∈ V_M(hat) and ⟨a, b⟩ ∈ V_M(in).

Rabbits

- *A rabbit is in a hat*
- $[\![\exists x(\text{rabbit}(x) \wedge \exists y(\text{hat}(y) \wedge \text{in}(x, y)))]\!]^{M,g} = 1$
  iff there is $a \in U_M$ such that $a \in V_M(\text{rabbit})$ and there is $b \in U_M$ such that $b \in V_M(\text{hat})$ and $\langle a, b\rangle \in V_M(\text{in})$.



$$
\begin{aligned}
M &= \langle U_M, V_M \rangle \\
U_M &= \{ r_1, r_2, h_1, h_2 \} \\
V_M(\text{rabbit}) &= \{ r_1, r_2 \} \\
V_M(\text{white}) &= \{ r_2 \} \\
V_M(\text{hat}) &= \{ h_1, h_2 \} \\
V_M(\text{in}) &= \{ (r_1, h_1) \}
\end{aligned}
$$

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.*
  - $\forall d\ (\text{dolphin}(d) \rightarrow$
    $\forall x\ \forall y\ \forall t\ (\text{give-birth-to}\ (d,x,t) \wedge \text{give-birth-to}\ (d,y,t)$
    $\rightarrow x = y)$

Research Questions in Semantics

- What is word meaning? How can it be represented and organised? How can it be acquired efficiently?
- What is sentence meaning and how can it be represented? How can it be composed from word meanings and syntactic information?
- How are semantic discourse representations built up from sequences of sentences?
- How does sentence meaning interact with context, yielding the intended utterance information?
- 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

- *Every firm saw costs grow more than expected, even after adjusting for inflation.*
  - $\models$ *Every large firm saw costs grow.*
- *At the end of the year, all solid companies pay dividends.*
  - $\models$ *At the end of the year, all solid insurance companies pay dividends.*
- *At the end of the year, all solid companies pay dividends.*
  - $\not\models$ *At the end of the year, all solid companies pay cash dividends.*

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

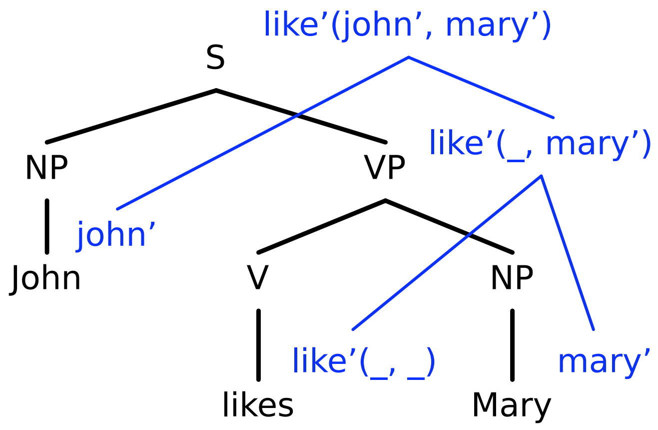
Research Questions in Semantics

- What is word meaning? How can it be represented and organised? How can it be acquired efficiently?
- What is sentence meaning and how can it be represented? How can it be composed from word meanings and syntactic information?
- How are semantic discourse representations built up from sequences of sentences?
- How does sentence meaning interact with context, yielding the intended utterance information?
- How can we infer the relevant information in the respective situation from the utterance information?

Semantics Construction

- The problem: Given a natural language sentence S, construct an appropriate logical expression that “captures” the truth-conditions of S.
- Basic idea: recursively walk through the syntax-tree of S and assign each syntax node X a semantic representation by combining the semantic representations of X’s children.

An Example



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 ⟨σ, τ⟩ made up of (basic or complex) types σ, τ are types. ⟨σ, τ⟩ 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 ∈ T, and if σ,τ ∈ T, then also ⟨σ,τ⟩ ∈ T.

Some Complex Types for Natural Language Semantics

- Individuals: e
- Sentences: t
- One-place predicate constants: ⟨e,t⟩
- Two-place relations: ⟨e,⟨e,t⟩⟩
- [...]

Type Theory – Vocabulary

- For every type τ
  - A possibly empty set of constants CON_τ
  - (infinite) sets of variables VAR_τ
- The usual predicate logic operators

Type Theory – Syntax

- 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 ¬A, (A∧B), (A∨B), (A→B), (A↔B)
  - If A is in WE_t, then so are ∀vA and ∃vA, where v is a variable of arbitrary type.
  - If α, β are well-formed expressions of the same type, then $\alpha=\beta \in WE_t$.

Type Theory – 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 ⟨σ,τ⟩ denote functions from denotations of type σ to denotations of type τ.

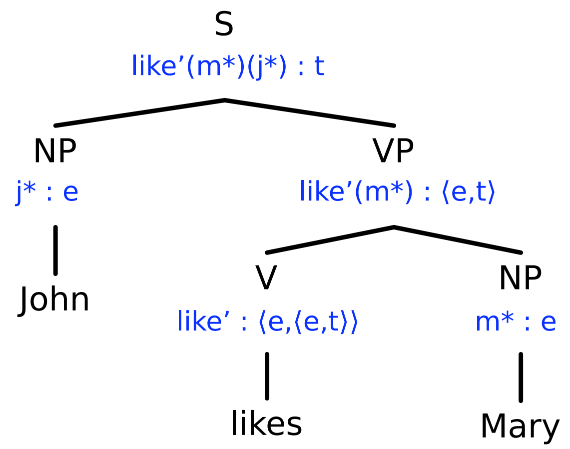
Type Theory – Examples

- *John loves Mary*
  - love(m)(j)
- *Every student works*
  - $\forall x(\text{student}(x) \rightarrow \text{work}(x))$
- *A white rabbit is in a hat*
  - $\exists x(\text{rabbit}(x) \wedge \text{white}(x) \wedge \exists y(\text{hat}(y) \wedge \text{in}(y)(x)))$
- *Dolphins live in pods.*
  - $\forall d(\text{dolphin}(d) \rightarrow \exists x\ (\text{pod}(p) \wedge \text{live-in}(p)(d)))$

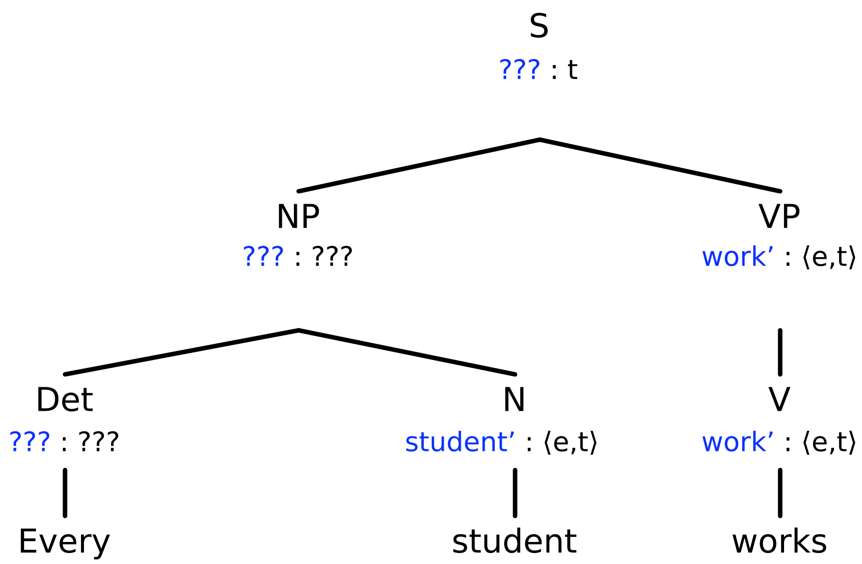
Beyond First Order

- *Peter is a brilliant student*
  - brilliant(student)(bill)
- *Peter and Mary have something in common*
  - $\exists P(P(\text{peter}) \wedge P(\text{mary}))$

Semantics Construction



"Every student works."



λ-Abstraction

- Syntax:
  - If $\alpha \in WE_\tau$ and $v \in VAR_\sigma$, then $\lambda v \alpha \in WE_{(\sigma,\tau)}$.
- Example:
  - λx(drive(x) ∧ drink(x))
- 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 ‘drive(x) ∧ drink(x)’ results in the complex predicate ‘λx(drive(x) ∧ drink(x)).’

β-Reduction

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

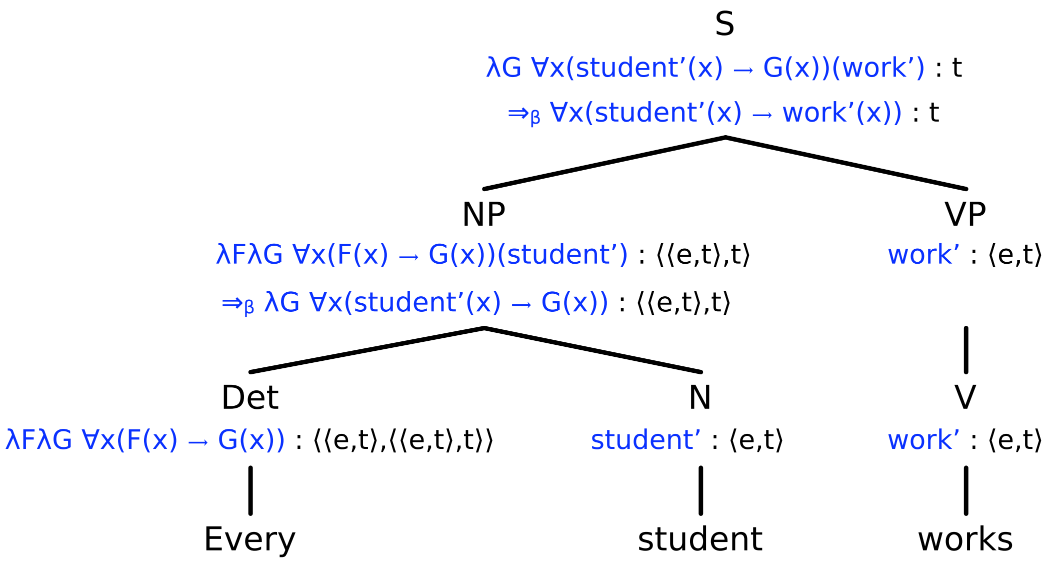
"John drinks and drives"

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

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

Research Questions in Semantics

- What is word meaning? How can it be represented and organised? How can it be acquired efficiently?
- What is sentence meaning and how can it be represented? How can it be composed from word meanings and syntactic information?
- How are semantic discourse representations built up from sequences of sentences?
- How does sentence meaning interact with context, yielding the intended utterance information?
- 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)