Foundations of Language Science and Technology

Semantics 4

Manfred Pinkal
Saarland University

The Story

- Modelling natural-language inference as deduction in a framework of truth-conditionally interpreted logic appears intuitive and straightforward.
- But: Logical methods are expensive and lack robustness and coverage.
- Corpus-based statistical methods for modelling inference are inexpensive and have no coverage problem.
- But: Shallow statistical models of inference are inherently imprecise and resist a satisfactory intuitive interpretation.
- But: There are highly promising approaches, which combine deep logic-based and shallow statistical methods.
- We will look at Bill MacCartney's doctoral dissertation on "Natural-language Inference" as one of the most interesting approaches.

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Negation and polarity

P: *Whooping cough, or pertussis, is a highly contagious bacterial infection characterized by violent coughing ts, gasp for air that resemble 'whoop' sounds, and vomiting*
H: *Pertussis is not very contagious.*

P: *Energy analysts said oil prices could soar as high as $80 a barrel, if damage reports from oil companies bear bad news.*
H: *Oil prices surged.*

General Tendencies of Results

- "Knowledge-lean" systems relying on shallow information (word overlap, string match, distributional similarity) perform better than naïve baseline of 50%, but only to some degree (60-65%).
- They may provide a good estimate of "aboutness": Is the Premiss/ text about the issue raised by the hypothesis?
- Systems relying on deep linguistic analysis and logical entailment perform drastically worse than naïve baseline (but are significantly more precise on cases they can treat).

- How can the best of deep and shallow methods be combined?

Textual Inference and Logical Inference

P: *Several airlines reported cost increases*

H: *Several companies reported cost increases*

- H can be obtained from P by a single substitution.
- *airlines* and *companies* stand in hyponymy relation
- From this, it clearly follows that P (logically) entails H - without a full logical analysis of the sentences.

More examples

P: *Several airlines polled reported cost increases*

H: *Several airlines reported cost increases*

- Deletion of modifiers preserves entailment.

P: *Several airlines polled reported cost increases*

H: *Several companies reported cost increases*

- Two entailment-inducing edits ad up to entailment again.

More examples

P: *Several airlines reported cost increases*

H: *Several airlines polled reported cost increases*

- Insertion (of modifiers) causes non-entailment (actually, it causes inverse entailment.

P: *Several airlines reported cost increases*

H: *Several companies polled cost increases*

- The combination of edits with opposite entailment effects leads to non-entailment (semantic independence) of P and H.

Example

P: *Several airlines polled saw costs grow more than expected.*

H: *Some companies reported cost increases.*

Atomic Edit		Lexical entailment		Sentence-level e.
SUB(*several, some*)	→	⊏	→	⊏
SUB(*airlines, companies*)	→	⊏	→	⊏
DEL(*polled*)	→	⊏	→	⊏
SUB(*saw, reported*)	→	≡ ?	→	≡
SUB(*costs, cost*)	→	≡	→	≡
SUB(*grow, increase*)	→	≡	→	≡
DEL(*more than expected*)	→	⊏	→	⊏

What we need

- A method to find the best or most appropriate alignment/ sequence of edit steps between P and H.
- A method to identify the specific lexical entailment relations induced by specific SUB edits; DEL and INS induce ⊏ and ⊐, respectively.
- A full specification of the join operation between entailment relations.
- A method to compute the effect of the lexical entailment relations on the logical entailment relation between full sentences - taking the context of the edits into account.

The effect of context

P: *John bought a new convertible.*
H: *John bought a new car.*

P: *John didn't buy a new convertible.*
H: *John didn't buy a new car.*

- In an affirmative standard context, a context with "positive polarity", an "upward monotonic" context, sentence-level entailment is atomic lexical entailment.
- In the context of a negation, a context with "negative polarity", a "downward monotonic" context, atomic lexical entailment is inverted on the sentence level.

Example contexts: Conditionals

P: If John will buy a new convertible, he will run into financial difficulties.

H: If John will buy a new car, he will run into financial difficulties.

P: If John will buy a new car, he will run into serious financial difficulties.

H: If John will buy a new car, he will run into financial difficulties.

Example contexts: Quantifiers

P: *No airline reported cost increases.*
P: *No company reported cost increases.*

P: *No airline reported extreme cost increases.*
P: *No airline reported cost increases.*

P: *All airlines reported cost increases.*
P: *All companies reported cost increases.*

P: *All airlines reported extreme cost increases.*
P: *All airlines reported cost increases.*

P: *Most airlines reported cost increases.*
P: *Most companies reported cost increases.*

P: *Most airlines reported extreme cost increases.*
P: *Most airlines reported cost increases.*

Example contexts: Verbs

P: Bill doubts whether John bought a new convertible.
H: Bill doubts whether John bought a new car.

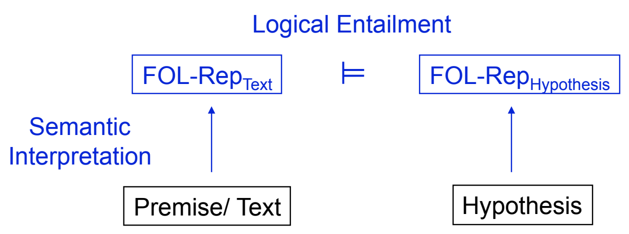
P: Bill doubts whether John bought a new convertible.
H: Bill doubts whether John bought a new car.

P: Bill refused to drive a convertible.
H: Bill refused to drive a car.

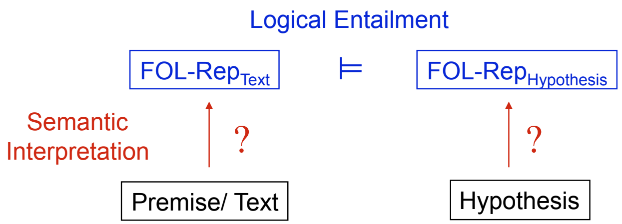
What we need

- A method to find the best or most appropriate alignment/ sequence of edit steps between P and H.
- A method to identify the specific lexical entailment relations induced by specific SUB edits; DEL and INS induce $\sqsubset$ and $\sqsupset$, respectively.
- A full specification of the join operation between entailment relations.
- A method to compute the effect of the lexical entailment relations on the logical entailment relation between full sentences - taking the context of the edits into account.

Logical Entailment



Logical Entailment



Compositionality

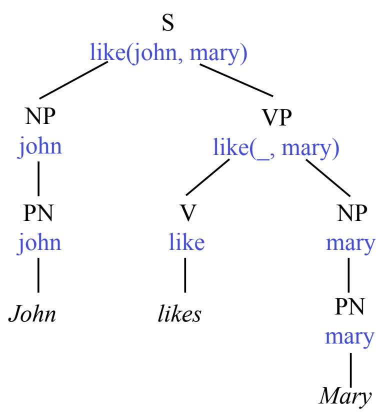
Frege's Principle:

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

- The model-theoretic interpretation of FOL is perfectly compositional in the sense of Frege's Principle.
- But: Is there a way to give a compositional semantic interpretation to natural-language expressions?
  Is there a "surface compositional interpretation" for natural language?

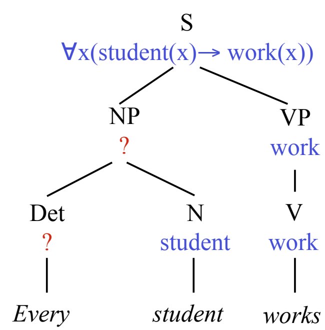
Composing FOL formulae

- *John likes Mary* ⇒ like(john, mary)



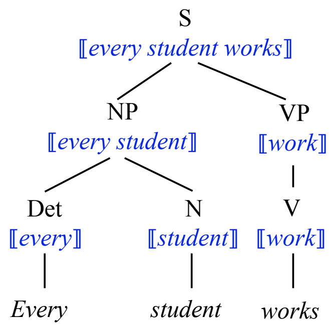
... doesn't work for quantification

- *Every student works* ⇒ ∀x(student(x)→ work(x))



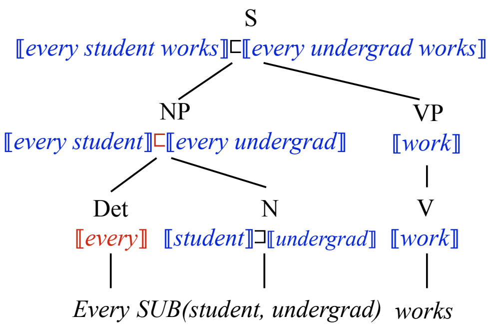
Direct interpretation of NL constituents

- *Every student works* ⇒ ∀x(student(x)→ work(x) ⟦⟧)



Entailment projection

- *Every student works* ⊨ *Every undergraduate works*



Entailment projection

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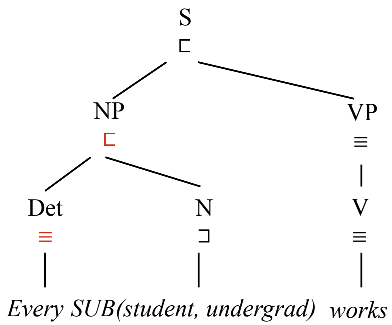

FOL: Lack of Expressiveness

John is a married piano player	piano-player(j) ∧ married(j)
John is a blond criminal	criminal(j) ∧ blond(j)
John is a poor piano player	piano-player(j) ∧ poor(j) ?
John is an alleged criminal	criminal(j) ∧ alleged(j) ???

FOL: Lack of Expressiveness

Yesterday, we had minus temperatures.
Probably, it will snow tomorrow.
Unfortunately, it is extremely cold.

Flipper is a dolphin. A dolphin is a mammal.

$\models$ *Flipper is a mammal.*

Bill is blond. Blond is a hair colour.

$\not\models$ *Bill is a hair colour.*

The Language of Type Theory

Types:

- 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$\in$**T**, and if $\sigma,\tau \in$**T**, then also $(\sigma,\tau) \in$**T.**

Some Useful Types for NL Semantics

- Proper name bill: e
- Sentence it_rains: t
- One-place predicate constant:
  work, student: <e,t>
- Two-place relation:
  like, larger_than: <e,<e,t>>
- Sentence adverbial:
  yesterday, unfortunately: <t,t>
- Attributive adjective:
  married, poor, alleged: <<e,t>,<e,t>>
- Degree modifier:
  very, relatively:
  <<<e,t>,<e,t>>,<<e,t>,<e,t>>>

Second-order predicates

Bill is blond. Blond is a hair colour.

bill: e blond: <e,t>

blond(bill): t

Blond is a hair colour.

blond: <e,t> hair_colour : <<e,t>,t>

hair_colour (blond): t

Bill is a hair colour ???

- Hair-colour is a second-order predicate. *hair_colour(bill)* is not even a well-formed expression.

Type-theoretic syntax

- Vocabulary:
  - A (possibly empty) set of constants: Con_τ, for every type τ
  - A set of variables: Var_τ, for every type τ
  - The usual FOL operators: connectives, quantifiers, equality
- The sets of well-formed expressions WE_τ for every type τ are given by:
  - $Con_\tau \cup Var_\tau \subseteq WE_\tau$ for every type τ
  - If $\alpha \in WE_{<\sigma, \tau>}$, $\beta \in WE_\sigma$, 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 $\forall v A$ and $\exists v A$, where v is a variable of arbitrary type.
  - If α, β are well-formed expressions of the same type, then $\alpha=\beta \in We_t$.

Function Application

- The most important syntactic operation in type-theory is function application:

  If $\alpha \in WE_{<\sigma, \tau>}$, $\beta \in WE_\sigma$, then $\alpha(\beta) \in WE_\tau$.

- Note: A functor of complex type combines with an appropriate argument to a yield a (more complex) expression of less complex type.

Function Application: Examples

Bill drives fast

drive: <e,t> fast: <<e,t>,<e,t>>

bill: e fast(drive): <e,t>

fast(drive)(bill): t

Mary works in Saarbrücken

in: <e, <<e,t>,<e,t>>> sb: e

work: <e,t> in(sb): <<<e,t>,<e,t>>>

mary: e work(in(sb))): <e,t>

work(in(sb)))

Using Higher-Order Variables

- *Bill has the same hair colour as John.*

  $\exists \mathcal{G}$ (hair_colour($\mathcal{G}$) $\wedge$ $\mathcal{G}$ (bill) $\wedge$ $\mathcal{G}$ (john))

- *Santa Claus has all the attributes of a sadist.*

  $\forall \mathcal{F} \forall a$(sadist(a) $\wedge$ $\mathcal{F}$ (a) $\rightarrow$ $\mathcal{F}$(b))

Type-theoretic semantics [1]

- Let U be a non-empty set of entities. The domain of possible denotations for every type τ, D_τ, is given by:
  - $D_e = U$
  - $D_t = \{0,1\}$
  - $D_{\langle\sigma,\tau\rangle}$ is the set of all functions from D_σ to D_τ

Example

- Let U consist of John, Bill, Mary, Paul, and Sally (persons, not proper names!)
  - $D_t = \{0,1\}$
  - $D_e = U = \{j, b, m, p, s\}$
  - $D_{\langle e,t\rangle} = \{ \begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 0 \\ s\to 1 \end{bmatrix}, \begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 1 \\ s\to 1 \end{bmatrix}, \begin{bmatrix} j\to 0 \\ b\to 1 \\ m\to 0 \\ p\to 0 \\ s\to 1 \end{bmatrix}, \ldots\}$

An element of $D_{\langle\langle e,t\rangle, \langle e,t\rangle\rangle}$

$$\begin{bmatrix} \begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 0 \\ s\to 1 \end{bmatrix} & \to & \begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 0 \\ s\to 0 \end{bmatrix} \\ \begin{bmatrix} j\to 0 \\ b\to 1 \\ m\to 0 \\ p\to 0 \\ s\to 1 \end{bmatrix} & \to & \begin{bmatrix} j\to 0 \\ b\to 0 \\ m\to 0 \\ p\to 0 \\ s\to 1 \end{bmatrix} \\ \begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 1 \\ s\to 1 \end{bmatrix} & \to & \begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 0 \\ s\to 0 \end{bmatrix} \\ & \ldots & \end{bmatrix}$$

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  - $D_t = \{0,1\}$
  - $D_{\langle\sigma,\tau\rangle}$ is the set of all functions from D_σ to D_τ
- A model structure for a type theoretic language:
  M = <U, V>, where
  - U (or U_M) is a non-empty domain of individuals
  - V (or V_M) is an interpretation function, which assigns to every member of Con_τ an element of D_τ.
- Variable assignment g assigns every variable of type τ a member of D_τ.

Interpretation function, examples

$V_M(\textit{john}) = j$ $\qquad V_M(\textit{mary}) = m$

$V_M(\textit{piano player})$: $\begin{bmatrix} j \to 1 \\ b \to 0 \\ m \to 1 \\ p \to 0 \\ s \to 1 \end{bmatrix}$ $\qquad V_M(\textit{semanticist})$: $\begin{bmatrix} j \to 0 \\ b \to 1 \\ m \to 0 \\ p \to 0 \\ s \to 1 \end{bmatrix}$

$V_M(\textit{skier})$: $\begin{bmatrix} j \to 1 \\ b \to 0 \\ m \to 1 \\ p \to 1 \\ s \to 1 \end{bmatrix}$

A predicate modifier

$$V_M(\textit{talented}): \begin{bmatrix} \begin{bmatrix} j \to 1 \\ b \to 0 \\ m \to 1 \\ p \to 0 \\ s \to 1 \end{bmatrix} \to \begin{bmatrix} j \to 1 \\ b \to 0 \\ m \to 1 \\ p \to 0 \\ s \to 0 \end{bmatrix} \\ \begin{bmatrix} j \to 0 \\ b \to 1 \\ m \to 0 \\ p \to 0 \\ s \to 1 \end{bmatrix} \to \begin{bmatrix} j \to 0 \\ b \to 0 \\ m \to 0 \\ p \to 0 \\ s \to 1 \end{bmatrix} \\ \begin{bmatrix} j \to 1 \\ b \to 0 \\ m \to 1 \\ p \to 1 \\ s \to 1 \end{bmatrix} \to \begin{bmatrix} j \to 1 \\ b \to 0 \\ m \to 1 \\ p \to 0 \\ s \to 0 \end{bmatrix} \\ \ldots \end{bmatrix}$$

Type-theoretic semantics [2]

- Interpretation (with respect to model structure M and variable assignment g):

  $[[\alpha]]^{M,g} = V_M(\alpha)$, if α constant

  $[[\alpha]]^{M,g} = g(\alpha)$, if α variable

  $[[\alpha(\beta)]]^{M,g} = [[\alpha]]^{M,g}([[\beta]]^{M,g})$

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

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

  If $v \in Var_\tau$, $[[\exists v\varphi]]^{M,g} = 1$ iff there is $a \in D_\tau$ such that $[[\varphi]]^{M,g[v/a]} = 1$

  If $v \in Var_\tau$, $[[\forall v\varphi]]^{M,g} = 1$ iff for all $a \in D_\tau$: $[[\varphi]]^{M,g[v/a]} = 1$

  $[[\alpha=\beta]]^{M,g} = 1$ iff $[[\alpha]]^{M,g} = [[\beta]]^{M,g}$

Example

John is a talented piano-player

$\Rightarrow$ talented(piano-player)(john)

$[[\text{talented(piano-player)(john)}]]^{M,g} =$

$[[\text{talented(piano-player)}]]^{M,g}([[\text{john}]]^{M,g}) =$

$[[\text{talented}]]^{M,g}([[\text{piano-player}]]^{M,g})([[\text{john}]]^{M,g}) = V_M$

$V_M(\text{talented})(V_M(\text{piano-player}))\ (V_M(\text{john}))$

Example continued:

V_M(*piano-player*)

V_M(*talented*):

$$\left[\begin{array}{ccc}
\begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 0 \\ s\to 1 \end{bmatrix} & \to & \begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 0 \\ s\to 0 \end{bmatrix} \\
\begin{bmatrix} j\to 0 \\ b\to 1 \\ m\to 0 \\ p\to 0 \\ s\to 1 \end{bmatrix} & \to & \begin{bmatrix} j\to 0 \\ b\to 0 \\ m\to 0 \\ p\to 0 \\ s\to 1 \end{bmatrix} \\
\begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 1 \\ s\to 1 \end{bmatrix} & \to & \begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 0 \\ s\to 0 \end{bmatrix} \\
 & \ldots &
\end{array}\right]$$

Example continued:

V_M(*piano-player*)

V_M(*talented*):

$$\left[\begin{array}{ccc}
\begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 0 \\ s\to 1 \end{bmatrix} & \to & \begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 0 \\ s\to 0 \end{bmatrix} \\
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\begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 1 \\ s\to 1 \end{bmatrix} & \to & \begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 0 \\ s\to 0 \end{bmatrix} \\
 & \ldots &
\end{array}\right]$$

V_M(*talented*)(V_M(*piano-player*))

Example continued:

V_M(*john*)

V_M(*piano-player*)

V_M(*talented*):

$$\left[\begin{array}{ccc}
\begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 0 \\ s\to 1 \end{bmatrix} & \to & \begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 0 \\ s\to 0 \end{bmatrix} \\
\begin{bmatrix} j\to 0 \\ b\to 1 \\ m\to 0 \\ p\to 0 \\ s\to 1 \end{bmatrix} & \to & \begin{bmatrix} j\to 0 \\ b\to 0 \\ m\to 0 \\ p\to 0 \\ s\to 1 \end{bmatrix} \\
\begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 1 \\ s\to 1 \end{bmatrix} & \to & \begin{bmatrix} j\to 1 \\ b\to 0 \\ m\to 1 \\ p\to 0 \\ s\to 0 \end{bmatrix} \\
 & \ldots &
\end{array}\right]$$

V_M(*talented*)(V_M(*piano-player*))(j)

V_M(*talented*)(V_M(*piano-player*))