Natural Language Processing

Lecture 19: Compositional Semantics and Semantic Parsing
Meaning

• The recent lectures dealt with some issues around word meaning, primarily:
  • Relationships between words and word similarity
  • Word sense disambiguation
  • Predicates and their arguments
• Today: meaning of NL (English) sentences
Key Challenge of Meaning

• We actually say very little - much more is left unsaid, because it’s assumed to be widely known.

• Examples:
  • Grading assignments
  • Restaurant menus
  • Learning to use a new piece of software
Meaning Representation Languages

• Symbolic representation that does two jobs:
  • Conveys the meaning of a sentence
  • Represents (some part of) the world

• Today we’ll use first-order logic.
A MRL Should Be Able To ...

- Verify a query against a knowledge base
  - Do CMU students follow politics?
- Eliminate ambiguity
  - CMU students enjoy visiting Senators.
- Cope with vagueness
  - Sally heard the news.
- Cope with many ways of expressing the same meaning (canonical forms)
  - The candidate evaded the question.
  - The question was evaded by the candidate.
- Draw conclusions based on the knowledge base
  - Who could become the 48th president?
- Represent all of the meanings we care about
Model-Theoretic Semantics

• Model: a simplified representation of the world: objects, properties, relations (domain).

• Non-logical vocabulary
  • Each element denotes a well-defined part of the model
  • Such a mapping is called an interpretation
A Model

- **Domain**: Noah, Karen, Rebecca, Frederick, Green Mango, Casbah, Udipi, Thai, Mediterranean, Indian
- **Properties**: Green Mango and Udipi are crowded; Casbah is expensive
- **Relations**: Karen likes Green Mango, Frederick likes Casbah, everyone likes Udipi, Green Mango serves Thai, Casbah serves Mediterranean, and Udipi serves Indian
- \( n, k, r, f, g, c, u, t, m, i \)
- Crowded = \{g, u\}
- Expensive = \{c\}
- Likes = \{(k, g), (f, c), (n, u), (k, u), (r, u), (f, u)\}
- Serves = \{(g, t), (c, m), (u, i)\}
Some English

• Karen likes Green Mango and Frederick likes Casbah.
• Noah and Rebecca like the same restaurants.
• Noah likes expensive restaurants.
• Not everybody likes Green Mango.

• What we want is to be able to represent these statements in a way that lets us compare them to our model.

• Truth-conditional semantics: need operators and their meanings, given a particular model.
First-Order Logic

- **Terms** refer to elements of the domain: **constants**, **functions**, and **variables**
  - Noah, SpouseOf(Karen), X

- **Predicates** are used to refer to sets and relations
  - Serves(Casbah, Mediterranean)

- Logical connectives: \( \land \) (and), \( \lor \) (or), \( \neg \) (not), \( \implies \) (implies), ...

- Quantifiers ...
Quantifiers in FOL

- Two ways to use variables:
  - refer to one anonymous object from the domain (existential; $\exists$; “there exists”)
  - refer to all objects in the domain (universal; $\forall$; “for all”)

- a restaurant near CMU that serves Indian food
  $\exists x \text{ Restaurant}(x), \text{Near}(x, \text{CMU}), \text{Serves}(x, \text{Indian})$

- All expensive restaurants are far from campus
  $\forall x \text{ Restaurant}(x), \text{Expensive}(x) \Rightarrow \neg \text{Near}(x, \text{CMU})$
Extension: Lambda Notation

• A way of making anonymous functions.
• \( \lambda x. (\text{some expression mentioning } x) \)
  • Example: \( \lambda x. \text{Near}(x, \text{CMU}) \)
  • Deeper example: \( \lambda x. \lambda y. \text{Serves}(y, x) \)
• Lambda reduction: substitute for the variable.
  • \( (\lambda x. \text{Near}(x, \text{CMU}))(\text{Lulu's Noodles}) \) becomes \( \text{Near}(\text{Lulu's Noodles}, \text{CMU}) \)
Inference

• Big idea: extend the knowledge base, or check some proposition against the knowledge base.

• **Forward chaining** with modus ponens:
  • given $\alpha$ and $\alpha \Rightarrow \beta$, we know $\beta$.

• **Backward chaining** takes a query $\beta$ and looks for propositions $\alpha$ and $\alpha \Rightarrow \beta$ that would prove $\beta$.
  • Not the same as backward reasoning (abduction).
  • Used by Prolog

• Both are sound, neither is complete.
Lots More To Say About MRLs!

• See chapter 17 for more about:
  • Representing events and states in FOL
  • Dealing with optional arguments (e.g., “eat”)
  • Representing time
  • Non-FOL approaches to meaning
First-Order Worlds, Then and Now

• Interest in this topic waned during the 1990s and 2000s.

• It’s come back, with the rise of semi-structured databases like Wikipedia.
  • Lay contributors to these databases may be helping us to solve the knowledge acquisition problem.

• Also, lots of research on using NLP, information extraction, and machine learning to grow and improve knowledge bases from free text data.
  • “Read the Web” project here at CMU.
Connecting Syntax and Semantics
Semantic Analysis

• Goal: transform a NL statement into MRL (today, FOL).

• We’re assuming a very literal, inference-free version of meaning!

• Sometimes called “semantic parsing.”
Compositionality

- The meaning of an NL phrase is determined by combining the meaning of its sub-parts.
- There are obvious exceptions ("hot dog," "straw man," "New York," etc.).
- Big idea: start with parse tree, build semantics on top using FOL with λ-expressions.
An Example

• Noah likes expensive restaurants.

• ∀x Restaurant(x), Expensive(x) ⇒ Likes(Noah, x)
• Noah likes expensive restaurants.

• ∀x Restaurant(x), Expensive(x) ⇒ Likes(Noah, x)
An Example

• Noah likes expensive restaurants.

• $\forall x \text{ Restaurant}(x), \text{ Expensive}(x) \Rightarrow \text{ Likes}(\text{Noah}, x)$
An Example

- Noah likes expensive restaurants.

\[ \lambda f. \lambda y. \forall x f(x) \Rightarrow Likes(y, x) \]

- \( \forall x \) Restaurant(x), Expensive(x) \( \Rightarrow \) Likes(Noah, x)
An Example

- Noah likes expensive restaurants.
- $\forall x \text{ Restaurant}(x), \text{Expensive}(x) \Rightarrow \text{Likes}(\text{Noah}, x)$
An Example

• Noah likes expensive restaurants.

• $\forall x \text{ Restaurant}(x), \text{ Expensive}(x) \Rightarrow \text{Likes}(\text{Noah}, x)$
An Example

• Noah likes expensive restaurants.

• \( \forall x \) Restaurant\( (x) \), Expensive\( (x) \) \( \Rightarrow \) Likes\( (Noah, x) \)
An Example

- Noah likes expensive restaurants.
- $\forall x \text{ Restaurant}(x), \text{ Expensive}(x) \Rightarrow \text{Likes}(\text{Noah}, x)$
An Example

- Noah likes expensive restaurants.
- $\forall x \text{ Restaurant}(x), \text{ Expensive}(x) \Rightarrow \text{Likes}(\text{Noah}, x)$

• Noah likes expensive restaurants.
• $\forall x \text{ Restaurant}(x), \text{ Expensive}(x) \Rightarrow \text{Likes}(\text{Noah}, x)$
Alternative (Following SLP)

• Noah likes expensive restaurants.

• $\forall x \text{ Restaurant}(x), \text{Expensive}(x) \Rightarrow \text{Likes}(\text{Noah}, x)$

$S \rightarrow \text{NP VP } \{ \text{NP.sem(VP.sem)} \}$
Quantifier Scope Ambiguity

• Every man loves a woman.

• $\forall u \text{ Man}(u) \Rightarrow \exists x \text{ Woman}(x) \land \text{ Loves}(u, x)$

• $\exists x \text{ Woman}(x) \land \forall u \text{ Man}(u) \Rightarrow \text{ Loves}(u, x)$
This Isn’t Quite Right!

• “Every man loves a woman” really is ambiguous.
  • A seat was available for every customer
  • A toll free number was available for every customer
  • A secretary phoned up each director
  • A letter was sent to each customer
• This gives only one of the two meanings.
• One approach is to delay the quantifier processing until the end, then permit any ordering.
Matching Syntax and Semantics

- Combinatorial Categorial Grammar (CCG)
- Five grammar rules (only)
  - Forward application \( A/B + B = A \)
  - Backward application: \( B + A\backslash B = A \)
  - Composition: \( A/B + B/C = A/C \)
  - Conjunction: \( A \text{ CONJ } A' = A \)
  - Type Raising \( A = X/(X\backslash A) \)
CCG Parsing

John = np
Mary = np
likes = (s\np)/np

Forward application
X/Y Y => X
Backward application
Y X\Y => X

Thus
John  likes  Mary
np   (s\np)/np   np
        -------- Forward
          s\np
        -------- Backward
          s
a, the np/n
old n/n
in (np\np)/np
man, ball, park n
kicked (s\np)/np

the old man kicked a ball in the park
np/n n/n n (s\np)/np np/n n (np\np)/np np/n n

n

np

np

np

np\np

np

np

s\np

s
CCG Parsing and Semantics

\[ A/B:S + B:T = A:S:T \]
\[ B:T + A\backslash B:S = A:S:T \]

John np:j
walks (s\np):lambda X walks(X)

John walks
np:j s\np:lambda X walks(X)

\[ \text{s: walks}^{(j)} \]

B:T + A\backslash B:S = A:S . T
np:j + s\np:lambda X walks(X)
s : lambda X walks(X) . j
s : walks^{(j)}
John np:j
Mary np:m
likes (s\np)/np: lambda Y lambda X likes(X,Y)

John np:j (s\np)/np: lambda Y lambda X likes(X,Y)  
-----------------------------
      s\np: lambda X likes(X,m)
-----------------------------
    s likes(j,m)

lambda Y lambda X likes(X,Y) . m
lambda X likes(X,m)

lambda X likes(X,m) . j
likes(j,m)
Probabilistic CCGs

• Derive lexical entries from data
  • Find which entries allow parsing (constrained)
• From data with logical forms
  • Find out possible parses that derived those forms
  • But needs sentence → logical form training data
• But can work on targeted domains
SEMAFOR

- Semantic parser (Das et al 2014)
- Uses FrameNET to identify frames
- Fills in roles for a sentence

But there still are n't enough ringers to ring more than six of the eight bells .