Computational Semantics

Deep Processing for NLP
Ling 571
February 9, 2015

Roadmap

- Motivation: Dialog Systems
- Key challenges
- Meaning representation
  - Representational requirements
  - First-order logic
    - Syntax & Semantics
  - Representing compositional meaning

Dialogue Systems

- User: What do I have on Thursday?
- Parse:
  - (S
  - (Q-WH-Obj
  - (Whwd What)
  - (Aux do)
  - (NP (Pron I))
  - (VP/NP (V have)
  - (NP/NP *t*)
  - (PP (Prep on)
  - (NP (N Thursday))))))

Dialogue Systems

- Parser:
  - Yes, it's grammatical!
  - Here's the structure!
- System: Great, but what am I supposed to DO?!

- Need to associate meaning with structure

Dialogue Systems

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- (Q-WH-Obj Action: check; cal: USER; Date:Thursday
- (Whwd What)
- (Aux do)
- (NP (Pron I)) Cal: USER
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Natural Language

- Syntax: Determine the structure of natural language input
- Semantics: Determine the meaning of natural language input

Tasks for Semantics

- Semantic interpretation required for many tasks
  - Answering questions
  - Following instructions in a software manual
  - Following a recipe
- Requires more than phonology, morphology, syntax
- Must link linguistic elements to world knowledge

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  - The protests had been peaceful.
  - Crowds oppose the government.
  - Some support Mubarak.
  - There was a confrontation between two groups.
  - Anti-government crowds are not Mubarak supporters.
  - Etc..

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- Meaning and action:
  - Meaning maps language into actions (robotics)
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- Semantics and models:
  - Meaning maps onto states in model theoretic ‘worlds’, e.g. Montague
    - Focuses on truth conditions of sentences, and their representation

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    - ‘kick the bucket’

More Challenges

- Semantic analysis:
  - How do we derive a representation of the meaning of an utterance?
  - AyCaramba serves meat. ->

$$\exists e\, Isa(e, Serving) \wedge Server(e, AyCaramba) \wedge Served(e, Meat)$$

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  - Developing methods for reasoning about these representations and performing inference from them

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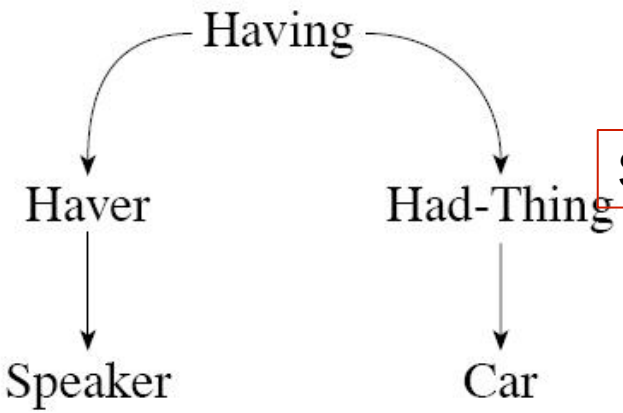
  - Reasoning: Given a representation and a world, what new conclusions – bits of meaning – can we infer?
- Effectively AI-complete
  - Need representation, reasoning, world model, etc

Representing Meaning

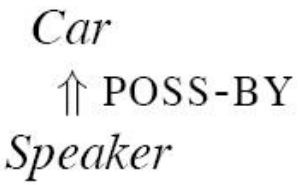
First-order Logic

$$\exists e, y\ Having(e) \wedge Haver(e, Speaker) \wedge HadThing(e, y) \wedge Car(y)$$

Semantic Network



Conceptual Dependency



Frame-Based

```
Having
 Haver:    Speaker
 HadThing: Car
```

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  - Representation of meaning of linguistic input
  - Representation of state of world
- Here we focus on **literal** meaning

Representational Requirements

- Verifiability
- Unambiguous representations
- Canonical Form
- Inference and Variables
- Expressiveness
  - Should be able to express meaning of any NL sent

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  - Description of state given by representation to
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  - If not, False or Don't Know
    - Is KB assumed complete or incomplete?

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- (Final) Representation must be unambiguous, e.g.,
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- Resolving the ambiguity?
  - Later

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- Single canonical form allows consistent verification

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  - Words: E.g, food, fare, dishes
    - Word senses, synonymy
    - Word sense disambiguation
  - Syntactic alternations:
    - E.g. active vs passive
    - Interrogative vs declarative forms, topicalization, etc

Inference

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- Linked by facts in the world
- *Inference* allows system to draw valid conclusions from meaning rep. and KB
  - Serves(Maharani,VegetarianFood) =>
  - CanEat(Vegetarians,AtMaharani)

Variables

- *I want a restaurant that serves vegetarian food.*
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- Solution:
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  - True if variable can be replaced by some object s.t. resulting proposition can match some assertion in KB

Meaning Structure of Language

- Human languages
  - Display basic predicate-argument structure
  - Employ variables
  - Employ quantifiers
  - Exhibit a (partially) compositional semantics

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- Subcategorization frames indicate:
  - Number, Syntactic category, order of args

Semantic Roles

- Roles of entities in an event
  - E.g. $\text{John}_{\text{AGENT}}$ hit $\text{Bill}_{\text{PATIENT}}$
- Semantic restrictions constrain entity types
  - The dog slept.
  - ?The rocks slept.
- Verb subcategorization links surface syntactic elements with semantic roles

First-Order Logic

- Meaning representation:
  - Provides sound computational basis for verifiability, inference, expressiveness
- Supports determination of propositional truth
- Supports compositionality of meaning
- Supports inference
- Supports generalization through variables

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    - *x, e*

FOL Representation

- **Predicates:**
  - Relations among objects
    - *Maharani serves vegetarian food.* ➔
    - *Serves(Maharani, VegetarianFood)*
    - *Maharani is a restaurant.* ➔
    - *Restaurant(Maharani)*

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    - *Serves(Maharani,VegetarianFood) ∧ Cheap(Maharani)*

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      $\exists x \, Restaurant(x) \wedge Serves(x, VegetarianFood) \wedge Cheap(x)$
  - ∀: universal quantifier: “for all”
    - All vegetarian restaurants serve vegetarian food.

      $\forall x \, VegetarianRestaurant(x) \Rightarrow Serves(x, VegetarianFood)$

FOL Syntax Summary

$$
\begin{array}{rcl}
\mathit{Formula} & \rightarrow & \mathit{AtomicFormula} \\
& | & \mathit{Formula\ Connective\ Formula} \\
& | & \mathit{Quantifier\ Variable}, \ldots\ \mathit{Formula} \\
& | & \neg\ \mathit{Formula} \\
& | & (\mathit{Formula}) \\
\mathit{AtomicFormula} & \rightarrow & \mathit{Predicate}(\mathit{Term}, \ldots) \\
\mathit{Term} & \rightarrow & \mathit{Function}(\mathit{Term}, \ldots) \\
& | & \mathit{Constant} \\
& | & \mathit{Variable} \\
\mathit{Connective} & \rightarrow & \wedge \mid \vee \mid \Rightarrow \\
\mathit{Quantifier} & \rightarrow & \forall \mid \exists \\
\mathit{Constant} & \rightarrow & A \mid \mathit{VegetarianFood} \mid \mathit{Maharani} \cdots \\
\mathit{Variable} & \rightarrow & x \mid y \mid \cdots \\
\mathit{Predicate} & \rightarrow & \mathit{Serves} \mid \mathit{Near} \mid \cdots \\
\mathit{Function} & \rightarrow & \mathit{LocationOf} \mid \mathit{CuisineOf} \mid \cdots
\end{array}
$$

Compositionality

- **Compositionality**: The meaning of a complex expression is a function of the meaning of its parts and the rules for their combination.
  - Formal languages are compositional.
  - Natural language meaning is largely, though not fully, compositional, but much more complex.
    - How can we derive things like loves(John, Mary) from John, loves(x,y), and Mary?

Lambda Expressions

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  - Just like lambda in Python, Scheme, etc
  - Allows abstraction over FOL formulas
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    - λ x.P(x) (A) → P(A)

λ-Reduction

- λ-reduction: Apply λ-expression to logical term
  - Binds formal parameter to term

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$$P(A)$$

- Equivalent to function application

Nested λ-Reduction

- Lambda expression as body of another

$$\lambda x.\lambda y.Near(x,y)$$

Nested λ-Reduction

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$$\lambda x.\lambda y.Near(x,y)$$

$$\lambda x.\lambda y.Near(x,y)(Bacaro)$$

Nested λ-Reduction

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$$\lambda y.Near(Bacaro,y)$$

Nested λ-Reduction

- Lambda expression as body of another

$$\lambda x.\lambda y.Near(x,y)$$

$$\lambda x.\lambda y.Near(x,y)(Bacaro)$$

$$\lambda y.Near(Bacaro,y)$$

$$\lambda y.Near(Bacaro,y)(Centro)$$

Nested λ-Reduction

- Lambda expression as body of another

$$\lambda x.\lambda y.Near(x,y)$$

$$\lambda x.\lambda y.Near(x,y)(Bacaro)$$

$$\lambda y.Near(Bacaro,y)$$

$$\lambda y.Near(Bacaro,y)(Centro)$$

$$Near(Bacaro,Centro)$$

Lambda Expressions

- Currying;
  - Converting multi-argument predicates to sequence of single argument predicates
  - Why?

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- Currying;
  - Converting multi-argument predicates to sequence of single argument predicates
  - Why?
    - Incrementally accumulates multiple arguments spread over different parts of parse tree

Semantics of Meaning Rep.

- Model-theoretic approach:
  - FOL terms (objects): denote elements in a domain
  - Atomic formulas are:
    - If properties, sets of domain elements
    - If relations, sets of tuples of elements
- Formulas based on logical operators:

P	Q	$\neg P$	$P \wedge Q$	$P \vee Q$	$P \Rightarrow Q$
False	*False*	*True*	*False*	*False*	*True*
False	*True*	*True*	*False*	*True*	*True*
True	*False*	*False*	*False*	*True*	*False*
True	*True*	*False*	*True*	*True*	*True*

- Compositionality provided by lambda expressions

Inference

- Standard AI-type logical inference procedures
  - Modus Ponens
  - Forward-chaining, Backward Chaining
  - Abduction
  - Resolution
  - Etc,..
- We'll assume we have a prover

Representing Events

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- Example:
  - I ate.
  - I ate a turkey sandwich.
  - I ate a turkey sandwich at my desk.
  - I ate at my desk.
  - I ate lunch.
  - I ate a turkey sandwich for lunch.
  - I ate a turkey sandwich for lunch at my desk.

Events

- Issues?

Events

- Issues?
  - Arity – how can we deal with different #s of arguments?

Events

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  - Arity – how can we deal with different #s of arguments?
- One predicate per frame
  - Eating_1(Speaker)
  - Eating_2(Speaker,TS)
  - Eating_3(Speaker,TS,Desk)
  - Eating_4(Speaker,Desk)
  - Eating_5(Speaker,TS,Lunch)
  - Eating_6(Speaker,TS,Lunch,Desk)

Events (Cont'd)

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  - Despite the names, actually unrelated predicates
    - Can't derive obvious info
      - E.g. I ate a turkey sandwich for lunch at my desk
        - Entails all other sentences

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        - Entails all other sentences
    - Can't directly associate with other predicates

Events (Cont'd)

- Good idea?
  - Despite the names, actually unrelated predicates
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    - Can't directly associate with other predicates
- Could write rules to implement implications
  - But?
    - Intractable in the large
      - Like the subcat problem generally.

Variabilizing

- Create predicate with maximum possible arguments
  - Include appropriate args
  - Maintains connections

$$\exists w, x, y Eating(Speaker, w, x, y)$$

$$\exists w, x Eating(Speaker, TS, w, x)$$

$$\exists w Eating(Speaker, TS, w, Desk)$$

$$Eating(Speaker, TS, Lunch, Desk)$$

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- Better?
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    - Can't individuate – don't know if same event

Events - Finalized

- Neo-Davidsonian representation:
  - Distill event to single argument for event itself
  - Everything else is additional predication

$$\exists e Eating(e) \wedge Eater(e, Speaker) \wedge Eaten(e, TS) \wedge Meal(e, Lunch) \wedge Location(e, Desk)$$

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- Pros:
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  - No extra roles
  - Logical connections can be derived

Meaning Representation for Computational Semantics

- Requirements:
  - Verifiability, Unambiguous representation, Canonical Form, Inference, Variables, Expressiveness
- Solution:
  - First-Order Logic
    - Structure
    - Semantics
    - Event Representation
- Next: Semantic Analysis
  - Deriving a meaning representation for an input

Summary

- First-order logic can be used as a meaning representation language for natural language
- Principle of compositionality: the meaning of a complex expression is a function of the meaning of its parts
- λ-expressions can be used to compute meaning representations from syntactic trees based on the principle of compositionality
- In the next lecture, we will look at a syntax-driven approach to semantic analysis in more detail