Meaning representations

Sharon Goldwater
(based on slides by Frank Keller, Bonnie Webber, Mirella Lapata, and others)

12 November 2019

Recap: distributional semantics

- A useful way to represent meanings of individual words
- Can deal with notions of similarity
- But less clear how to deal with compositionality
- Also, we still haven't discussed how to do **inference**

Example Question (6)

- Question

  Did Poland reduce its carbon emissions since 1989?

- Text available to the machine

  Due to the collapse of the industrial sector after the end of communism in 1989, all countries in Central Europe saw a fall in carbon emmissions.

  Poland is a country in Central Europe.

- What is hard?
  - we need to do inference
  - a problem for sentential, not lexical, semantics

Meaning representations

- Vector space is one kind of meaning representation. But not obvious how to deal with compositionality or inference.
- Instead, we can do this with representations that are **symbolic** and **structured**.
- Next lecture, **semantic analysis**: how to get from sentences to their meaning representations (using syntax to help).
- But first we need to define the semantics we're aiming at, i.e., a **meaning representation language** (MRL).

Basic assumption

The symbols in our meaning representations correspond to objects, properties, and relations *in the world*.

- *The world* may be the real world, or (usually) a formalized and well-specified world: a **model** or knowledge base of known facts.
  - Ex 1: a tiny world model containing 3 entities, and an exhaustive table of 'who loves whom' relations.
  - Ex 2: GeoQuery database [1], containing ∼800 facts about US geography.
  - Ex 3: Freebase [2], "A community-curated database of well-known people, places, and things" with over 2.6 billion facts.

[1] http://www.cs.utexas.edu/users/ml/nldata/geoquery.html, [2] https://www.freebase.com/

What do we want from an MRL?

Compositional: The meaning of a complex expression is a function of the meaning of its parts and of the rules by which they are combined.

What do we want from an MRL?

Compositional: The meaning of a complex expression is a function of the meaning of its parts and of the rules by which they are combined.

Verifiable: Can use the MR of a sentence to determine whether the sentence is *true* with respect to some given model of the world.

- In Ex 1 above, can establish the truth value of everybody loves Mary by checking it against the model.

What do we want from an MRL?

Unambiguous: an MR should have exactly one interpretation. So, an ambiguous sentence should have a different MR for each sense.

- Ex: each interpretation of I made her duck or time flies like an arrow should have a distinct MR.

- The job of producing all possible MRs for a given sentence will go to the semantic analyzer.

- We also defer the question of choosing which interpretation is correct.

What do we want from an MRL?

Canonical form: sentences with the same (literal) meaning should have the same MR.

- Ex: I filled the room with balloons should have the same canonical form as I put enough balloons in the room to fill it from floor to ceiling.
- Ex: Similarly, Tanjore serves vegetarian food and Vegetarian dishes are served by Tanjore.
- Simplifies inference and reduces storage needs; but also makes semantic analysis harder.

What do we want from an MRL?

Inference: we should be able to verify sentences not only directly, but also by drawing conclusions based on the input MR and facts in the knowledge base.

- Ex: from the MR for a query

  Did Poland reduce its carbon emissions?

- and the MRs for facts

  Carbon emmissions have fallen for all countries in Central Europe.

  Poland is a country in Central Europe.

- we should be able to infer the answer: YES.

What do we want from an MRL?

Expressivity: the MRL should allow us to handle a wide range of meanings and express appropriate relationships between the words in a sentence.

- Ideally, we could express the meaning of any natural language sentence.
- In practice, we may use simpler MRLs that cover a lot of what we want.
- For example...

FOL: First-order Logic (Predicate Logic)

- A pretty good fit to what we'd like.
- Example FOL expressions:
  - $\text{tall(Kim)} \vee \text{tall(Pierre)}$
  - $\text{likes(Sam, owner-of(Tanjore))}$
  - $\exists x.\text{cat}(x) \wedge \text{owns(Marie},x)$
  - $\exists x.\ \text{movie}(x) \wedge \forall y.\ \text{person}(y) \Rightarrow \text{loves}(y, x)$

FOL: First-order Logic (Predicate Logic)

- Expressions are constructed from **terms**:
  - **constant and variable symbols** that represent entities
  - **function symbols** that allow us to indirectly specify entities
  - **predicate symbols** that represent properties of entities and relations between entities

FOL: First-order Logic (Predicate Logic)

- Expressions are constructed from **terms**:
  - **constant and variable symbols** that represent entities
  - **function symbols** that allow us to indirectly specify entities
  - **predicate symbols** that represent properties of entities and relations between entities
- Terms can be combined into **predicate-argument structures**, which in turn are combined into complex expressions using:
  - **Logical connectives**: $\vee$, $\wedge$, $\neg$, $\Rightarrow$
  - **Quantifiers**: $\forall$ (universal quantifier, i.e., "for all"), $\exists$ (existential quantifier, i.e. "exists")

Constants in FOL

- Each constant symbol denotes exactly one entity:

  Scotland, EU, John, 2014

- Not all entities have a constant that denotes them:

  Lady Gaga's right knee, this pen

- Several constant symbols may denote the same entity:

  The Evening Star $\equiv$ Venus
  Scotland $\equiv$ Alba

Predicates in FOL

- Predicates with one argument represent properties of entities:

  nation(Scotland), organization(EU), tall(John)

- Predicates with multiple arguments represent relations between entities:

  member-of(UK, EU), likes(John, Marie), introduced(John, Marie, Sue)

- We write "/N" to indicate that a predicate has **arity** N (takes N arguments)

  member-of/2, nation/1, tall/1, introduced/3

The semantics of predicates

- A predicate of arity N denotes the set of N-tuples that satisfy it.
  - likes/2 is the set of (x, y) pairs for which likes(x, y) is true.
  - In the following example world, a set of four pairs:

likes(John, Marie)	likes(Marie, Kim)	tall(Kim)
likes(John, Kim)	eats(Marie, pizza)	nation(UK)
likes(Kim, UK)	lives-in(Marie, UK)	nation(USA)

- If all arguments are instantiated, then the predicate-argument structure has a truth value (determined by comparing it to the set of facts in the world).
  - So, likes(John, Kim) is true, whereas likes(John, UK) is false.

Functions in FOL

- Like constants, are used to specify (denote) unique entities.
- Unlike constants, they refer to entities indirectly, so we don't need to store as many constants.

  president(EU), father(John), right-knee(Gaga)

- Syntactically, they look like unary predicates, but denote entities, not sets.

Logical connectives

- Given FOL expressions P and Q, the meaning of an expression containing P and Q is determined from the meaning of each part and the logical connective.

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*

- True or false: Sharon is an MSc student $\Rightarrow$ Sharon is Chinese

Logical connectives

- Given FOL expressions P and Q, the meaning of an expression containing P and Q is determined from the meaning of each part and the logical connective.

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*

- True or false: Sharon is an MSc student $\Rightarrow$ Sharon is Chinese
- **True**, because the **antecedent** is **false**.

Variables in FOL

- Variable symbols (e.g., x, y, z) range over entities.
- An expression consisting only of a predicate with a variable among its arguments is interpreted as a set:

  $\text{likes}(x, \text{Kim})$ is the set of entities that like Kim.
- A predicate with a variable among its arguments only has a truth value if it is **bound** by a quantifier.

  $\forall x.\text{likes}(x, \text{Kim})$ has an interpretation as either true or false.

Universal Quantifier ($\forall$)

- Can be used to express general truths:

  Cats are mammals has MR $\forall x.\text{cat}(x) \Rightarrow \text{mammal}(x)$
- This MR is true iff the *conjunction* of *all* similar expressions is true, where each of these **substitutes** a differerent constant for the variable.

  $(\text{cat}(\text{Sam}) \Rightarrow \text{mammal}(\text{Sam})) \wedge$
  $(\text{cat}(\text{Zoot}) \Rightarrow \text{mammal}(\text{Zoot})) \wedge$
  $(\text{cat}(\text{Whiskers}) \Rightarrow \text{mammal}(\text{Whiskers})) \wedge$
  $(\text{cat}(\text{UK}) \Rightarrow \text{mammal}(\text{UK})) \wedge$
  $\ldots$

Existential Quantifier ($\exists$)

- Used to express that a property/relation is true of some entity, without specifying which one:

  Marie owns a cat has MR $\exists x.\text{cat}(x) \wedge \text{owns}(\text{Marie}, x)$
- This MR is true iff the *disjunction* of *all* similar expressions is true, where each of these **substitutes** a differerent constant for the variable.

  $(\text{cat}(\text{Sam}) \wedge \text{owns}(\text{Marie}, \text{Sam})) \vee$
  $(\text{cat}(\text{Zoot}) \wedge \text{owns}(\text{Marie}, \text{Zoot})) \vee$
  $(\text{cat}(\text{Whiskers}) \wedge \text{owns}(\text{Marie}, \text{Whiskers})) \vee$
  $(\text{cat}(\text{UK}) \wedge \text{owns}(\text{Marie}, \text{UK})) \vee$
  $\ldots$

Existential Quantifier ($\exists$)

- Why use $\wedge$ not $\Rightarrow$? Notice the difference between these two MRs:

  $\exists x.\text{cat}(x) \wedge \text{own}(\text{Marie}, x)$ vs $\exists x.\text{cat}(x) \Rightarrow \text{own}(\text{Marie}, x)$

  In English:

  There is something that is a cat and Marie owns it vs
  There is something that if it's a cat, Marie owns it
- $P \Rightarrow Q$ is true if the antecedent (left of the $\Rightarrow$) is false.
- So the righthand MR is true if there is anything that's not a cat!
  - If $\text{cat}(\text{UK})$ is false, then $\text{cat}(\text{UK}) \Rightarrow \text{owns}(\text{Marie}, \text{UK})$ is true, and so is $\exists \text{x}.\text{cat}(\text{x}) \Rightarrow \text{own}(\text{Marie}, \text{x})$.

Quantifier scoping

- Consider the following sentence:

  Everyone loves some movie

  – No ambiguity in POS tags, syntactic structure, or word senses.
  – But this sentence is still ambiguous!

Quantifier scoping

- Consider the following sentence:

  Everyone loves some movie

  – No ambiguity in POS tags, syntactic structure, or word senses.
  – But this sentence is still ambiguous!

- Two possible meanings:

  (a) There is a single movie that everyone loves
  (b) Everyone loves at least one movie, but the movies might be different

- This kind of ambiguity is called **quantifier scope ambiguity**

Quantifier scope ambiguity

- The two meanings have different MRs:

  (a) $\exists x.\ \text{movie}(x) \wedge (\forall y.\ \text{person}(y) \Rightarrow \text{loves}(y, x))$
  (b) $\forall y.\ \text{person}(y) \Rightarrow (\exists x.\ \text{movie}(x) \wedge \text{loves}(y, x))$

- In (a), the '$\exists$' has **scope** over the '$\forall$'; in (b) it's vice versa.

- Other examples of quantifier scope ambiguity:

  A boy gave flowers to each teacher
  Every cat chased a dog

Are we done?

- MRs in FOL are verifiable, unambiguous, canonical.

- Predicate-argument structure is a good match for natural language

  – Predicate-like elements: verbs, prepositions, adjectives
  – Argument-like elements: nouns, NPs

- Determiners (a, some, every) and coordination (if, and, or) can often be expressed with logical connectives and quantifiers.

- But what about compositionality?

Compositionality

- Suppose we have the following words with the following meanings:

word	meaning
Marie	*Marie*
pizza	*pizza*
loves	*love(x,y)*

- How do we get from there to the meaning of the sentence Marie loves pizza?

Lambda (λ) Expressions

- Extension to FOL, allows us to work with 'partially constructed' formulae.

- A λ-expression consists of:
  - the Greek letter λ, followed by a variable (**formal parameter**);
  - a FOL expression that may involve that variable.

$\lambda x.sleep(x)$	'The function that takes an entity x to the FOL expression $sleep(x)$'

- This lambda is the same one used in Python!

λ-Reduction

- A λ-expression can be **applied** to a **term**

$$\underbrace{\lambda x.sleep(x)}_{functor}\underbrace{(Marie)}_{argument}$$

- This expression can be simplified using **λ-reduction**: replace the formal parameter with the term and remove the λ. Result:

$$sleep(Marie)$$

Nested λ-expressions

- Use one λ-expression as the body of another.

- Allows predicates with several arguments to accept them one by one.

$\lambda y.\ \lambda x.\ love(x,y)$	'The function that takes y to (the function that takes x to the FOL expression $love(x,y)$)'
$\lambda z.\ \lambda y.\ \lambda x.\ give(x,y,z)$	'The function that takes z to (the function that takes y to (the function that takes x to the FOL expression $give(x,y,z)$))'

Nested λ-reduction

- Starting from binary predicate *λy. λx. love(x,y)*
- Apply to first argument:

  λy. λx. love(x,y) (pizza) becomes *λx. love(x, pizza)*

- Apply to second argument:

  λx. love(x, pizza) (Marie) becomes *love(Marie, pizza)*

Summary

- First-order logic can be used as a meaning representation language for natural language.
- λ-expressions can be used to compute meaning representations compositionally.
- Next time, we will see how to use these tools in a syntax-driven approach to semantic analysis.

Questions and exercises

1. Are the following statements true or false in the world on slide 16?

   (a) likes(John, Kim) $\wedge$ tall(John)
   (b) likes(John, Kim) $\wedge$ tall(Kim)
   (c) tall(John) $\Rightarrow$ likes(John, UK)
   (d) tall(Kim) $\Rightarrow$ likes(Kim, UK)
   (e) tall(Kim) $\Rightarrow$ likes(John, UK)
   (f) $\forall x$.tall(x) $\Rightarrow$ likes(x, UK)
   (g) $\forall x$.likes(John, x) $\Rightarrow$ tall(x)
   (h) $\forall x$.tall(x) $\Rightarrow$ likes(John, x)
   (i) $\exists x$.likes(John, x) $\wedge$ tall(x)
   (j) $\exists x$.likes(UK, x) $\Rightarrow$ tall(x)

2. Express each of the statements above in English. Try to make your English sentence as natural as possible. For example, one of the statements above could be expressed as "Everyone that John likes is tall."