Natural Language Processing

Info 159/259
Lecture 18: Semantic roles (March 31, 2020)

David Bamman, UC Berkeley
Why is syntax important?

• Foundation for semantic analysis (on many levels of representation: semantic roles, compositional semantics, frame semantics)

I bought a car from the salesperson

http://demo.ark.cs.cmu.edu
Why is syntax insufficient?

• Syntax encodes the structure of language but doesn’t directly address meaning.

• Syntax alone doesn’t ground “grab” in an action to take in the world.
Lexical semantics

• Vector representation that encodes information about the distribution of contexts a word appears in.

• Words that appear in similar contexts have similar representations (and similar meanings, by the distributional hypothesis).

• We can represent what individual words “mean” as a function of what other words they’re related to (but that’s still not grounding).
Lexical semantics

<table>
<thead>
<tr>
<th>Word</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>grab</td>
<td>1</td>
</tr>
<tr>
<td>throw</td>
<td>0.824</td>
</tr>
<tr>
<td>pull</td>
<td>0.818</td>
</tr>
<tr>
<td>knock</td>
<td>0.799</td>
</tr>
<tr>
<td>grabbing</td>
<td>0.789</td>
</tr>
<tr>
<td>steal</td>
<td>0.787</td>
</tr>
<tr>
<td>pulling</td>
<td>0.764</td>
</tr>
<tr>
<td>grabs</td>
<td>0.756</td>
</tr>
<tr>
<td>away</td>
<td>0.746</td>
</tr>
<tr>
<td>catch</td>
<td>0.74</td>
</tr>
</tbody>
</table>
• “Grab” = execute GrabbingFunction()

• “the cup” = object ID 9AF1948A81CD22
Semantics

Lexical semantics is concerned with representing the meaning of words (and their relations).

Logical semantics is concerned with representing the meaning of sentences.
Meaning representation

A meaning representation should be *unambiguous*; each statement in a meaning representation should have one meaning.
Meaning representation

Syntax resolves some ambiguity
“Once every hour, someone is involved in an Internet scam”

“That person is Michael Scott”
Same structure for “someone” meaning:

- Each person for each scam
- One person in the same scam (Michael Scott)
First-order logic (FOL)

- We want to represent every sentence as an unambiguous proposition in FOL

<table>
<thead>
<tr>
<th>Sentence</th>
<th>Luke was fighting with Darth Vader</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOL</td>
<td>FIGHT(LUKE, VADER)</td>
</tr>
</tbody>
</table>
This is a *relation*; we define what it means

These are *constants*; we know who they uniquely identify
First-order logic (FOL)

- How we map a natural language sentence to FOL is the task of semantic parsing; but we define the FOL relations and entities to be sensitive to what matters in our model.

<table>
<thead>
<tr>
<th>Sentence</th>
<th>FOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luke fought with Vader</td>
<td></td>
</tr>
<tr>
<td>Skywalker dueled with Darth Vader</td>
<td></td>
</tr>
<tr>
<td>Luke was fighting with Darth Vader</td>
<td></td>
</tr>
<tr>
<td>FOL</td>
<td></td>
</tr>
</tbody>
</table>
First-order logic (FOL)

- How we map a natural language sentence to FOL is the task of semantic parsing; but we define the FOL relations and entities to be sensitive to what matters in our world model.

<table>
<thead>
<tr>
<th>Sentence</th>
<th>FOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luke battled Vader</td>
<td>\textsc{Fight}(\textsc{Luke}, \textsc{Vader})</td>
</tr>
<tr>
<td>Luke fought with Vader</td>
<td>Luke was fighting with Darth Vader</td>
</tr>
<tr>
<td>Skywalker dueled with Darth Vader</td>
<td>FOL</td>
</tr>
</tbody>
</table>

Maybe in our star wars model we want to preserve the difference between fighting and dueling.
First-order logic (FOL)

- How we map a natural language sentence to FOL is the task of semantic parsing; but we define the FOL relations and entities to be sensitive to what matters in our world model.

For a robot model, there is only one possible “grabbing” kind of action, so subtle differences don’t matter.

<table>
<thead>
<tr>
<th>Sentence</th>
<th>Grab the cup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sentence</td>
<td>Snatch the cup!</td>
</tr>
<tr>
<td>Sentence</td>
<td>Take the cup</td>
</tr>
<tr>
<td>FOL</td>
<td>\textbf{GRAB} (Robot, Cup)</td>
</tr>
</tbody>
</table>
N-ary relations hold among FOL terms (constants, variables, functions).

<table>
<thead>
<tr>
<th>Unary (property)</th>
<th>HUMAN(LUKE), ROBOT(C-3PO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>binary relation</td>
<td>FIGHTS(LUKE, VADER)</td>
</tr>
<tr>
<td>ternary</td>
<td>GIVES(OBI-WAN, LUKE, LUKE_LIGHTSABER_1)</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Event semantics

Pat gives Sal a book

$\exists x. \text{book}(x) \land \text{GIVE}(\text{Pat}, \text{Sal}, x)$
Event semantics

Yesterday, Pat gave Sal a book reluctantly

\[ \exists x. \text{book}(x) \land \text{GIVE}(\text{Pat, Sal, } x, \text{ yesterday, reluctantly}) \]

• One option: extend the arity of the relation (require more arguments)
• But that’s not great because we need a separate predicate for every possible combination of arguments (even those that aren’t required).
Event semantics

We can reify the event to an existentially quantified variable of its own, and then use it as an argument in other relations.

\[ \exists e, x. \text{GIVE-EVENT}(e) \]
\[ \land \text{GIVER}(e, \text{Pat}) \]
\[ \land \text{GIFT}(e, x) \]
\[ \land \text{BOOK}(x) \]
\[ \land \text{RECIPIENT}(e, \text{Sal}) \]
\[ \land \text{TIME}(e, \text{yesterday}) \]
\[ \land \text{MANNER}(e, \text{reluctantly}) \]
Event semantics

Neo-Davidson event semantics: the event is central, and relations are predicated of the event. Each argument of an event holds its own relation.

\[ \exists e, x. \text{GIVE-EVENT}(e) \]
\[ \land \text{GIVER}(e, Pat) \]
\[ \land \text{GIFT}(e, x) \]
\[ \land \text{BOOK}(x) \]
\[ \land \text{RECIPIENT}(e, Sal) \]
\[ \land \text{TIME}(e, yesterday) \]
\[ \land \text{MANNER}(e, reluctantly) \]

In model-theoretic semantics, each of these has a denotation in a world model.
Event semantics

Sasha broke the window

\[ \exists e, y. \text{BREAKING-EVENT}(e) \]
\[ \land \text{BREAKER}(e, \text{Sasha}) \]
\[ \land \text{BROKEN-THING}(e, y) \]
\[ \land \text{WINDOW}(y) \]

Pat opened the door

\[ \exists e, y. \text{OPENING-EVENT}(e) \]
\[ \land \text{OPENER}(e, \text{Pat}) \]
\[ \land \text{OPENED-THING}(e, y) \]
\[ \land \text{DOOR}(y) \]
Event semantics

In model-theoretic semantics, each of these has some denotation in the world model.

Example: WINDOW has a identifier in some knowledge base (e.g., Freebase) uniquely identifying its properties.

\[ \exists e, y. \text{BREAKING-EVENT}(e) \]
\[ \land \text{BREAKER}(e, \text{Sasha}) \]
\[ \land \text{BROKEN-THING}(e, y) \]
\[ \land \text{WINDOW}(y) \]

\[ \exists e, y. \text{OPENING-EVENT}(e) \]
\[ \land \text{OPENER}(e, \text{Pat}) \]
\[ \land \text{OPENED-THING}(e, y) \]
\[ \land \text{DOOR}(y) \]
Event semantics

This requires a comprehensive representation of the world

\[ \exists e, y. \text{BREAKING-EVENT}(e) \]
\[ \land \text{BREAKER}(e, \text{Sasha}) \]
\[ \land \text{BROKEN-THING}(e, y) \]
\[ \land \text{WINDOW}(y) \]

\[ \exists e, y. \text{OPENING-EVENT}(e) \]
\[ \land \text{OPENER}(e, \text{Pat}) \]
\[ \land \text{OPENED-THING}(e, y) \]
\[ \land \text{DOOR}(y) \]
Shallow semantics

\[ \exists e, y. \text{EVENT}(e) \]
\[ \land \; \text{CAUSER-OF-ACTION}(e, \text{Sasha}) \]
\[ \land \; \text{RECIPIENT-OF-ACTION}(e, y) \]
\[ \land \; \text{“window”}(y) \]

\[ \exists e, y. \text{EVENT}(e) \]
\[ \land \; \text{CAUSER-OF-ACTION}(e, \text{Pat}) \]
\[ \land \; \text{RECIPIENT-OF-ACTION}(e, y) \]
\[ \land \; \text{“door”}(y) \]

\[ \exists e, y. \text{BREAKING-EVENT}(e) \]
\[ \land \; \text{BREAKER}(e, \text{Sasha}) \]
\[ \land \; \text{BROKEN-THING}(e, y) \]
\[ \land \; \text{WINDOW}(y) \]

\[ \exists e, y. \text{OPENING-EVENT}(e) \]
\[ \land \; \text{OPENER}(e, \text{Pat}) \]
\[ \land \; \text{OPENED-THING}(e, y) \]
\[ \land \; \text{DOOR}(y) \]

These roles have a lot in common: direct causal responsibility for the events, have volition, often animate.
Shallow semantics

\[ \exists e, y. \text{EVENT}(e) \land \text{AGENT}(e, \text{Sasha}) \land \text{THEME}(e, y) \land \text{"window"}(y) \]

\[ \exists e, y. \text{EVENT}(e) \land \text{AGENT}(e, \text{Pat}) \land \text{THEME}(e, y) \land \text{"door"}(y) \]

\[ \exists e, y. \text{BREAKING-EVENT}(e) \land \text{BREAKER}(e, \text{Sasha}) \land \text{BROKEN-THING}(e, y) \land \text{WINDOW}(y) \]

\[ \exists e, y. \text{OPENING-EVENT}(e) \land \text{OPENER}(e, \text{Pat}) \land \text{OPENED-THING}(e, y) \land \text{DOOR}(y) \]
Shallow semantics

Agent: Sasha
Theme: window

Agent: Pat
Theme: door

\[ \exists e, y. \text{OPENING-EVENT}(e) \]
\[ \land \text{OPENER}(e, Pat) \]
\[ \land \text{OPENED-THING}(e, y) \]
\[ \land \text{DOOR}(y) \]

\[ \exists e, y. \text{BREAKING-EVENT}(e) \]
\[ \land \text{BREAKER}(e, Sasha) \]
\[ \land \text{BROKEN-THING}(e, y) \]
\[ \land \text{WINDOW}(y) \]
Thematic roles

Thematic roles capture the semantic commonality among arguments for different relations (predicates)

- John broke the window
- The window was broken by John

Different syntactic roles, but the same thematic role.
## Thematic roles

<table>
<thead>
<tr>
<th>Role</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agent</td>
<td>The volitional causer of an event</td>
</tr>
<tr>
<td>Experiencer</td>
<td>The experiencer of an event</td>
</tr>
<tr>
<td>Force</td>
<td>The non-volitional causer of the event</td>
</tr>
<tr>
<td>Theme</td>
<td>The participant most directly affected by an event</td>
</tr>
<tr>
<td>Result</td>
<td>The end product of an event</td>
</tr>
<tr>
<td>Content</td>
<td>The proposition or content of a propositional event</td>
</tr>
<tr>
<td>Instrument</td>
<td>An instrument used in an event</td>
</tr>
<tr>
<td>Beneficiary</td>
<td>The beneficiary of an event</td>
</tr>
<tr>
<td>Source</td>
<td>The origin of the object of a transfer event</td>
</tr>
<tr>
<td>Goal</td>
<td>The destination of an object of a transfer event</td>
</tr>
</tbody>
</table>
## Thematic roles

<table>
<thead>
<tr>
<th>Role</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agent</td>
<td><em>The waiter</em> spilled the soup.</td>
</tr>
<tr>
<td>Experiencer</td>
<td><em>John</em> has a headache.</td>
</tr>
<tr>
<td>Force</td>
<td><em>The wind</em> blows debris from the mall into our yards.</td>
</tr>
<tr>
<td>Theme</td>
<td>Only after Benjamin Franklin broke <em>the ice</em>...</td>
</tr>
<tr>
<td>Result</td>
<td>The city built <em>a regulation-size baseball diamond</em>...</td>
</tr>
<tr>
<td>Content</td>
<td>Mona asked “You met Mary Ann at a supermarket?”</td>
</tr>
<tr>
<td>Instrument</td>
<td>He poached catfish, stunning them with <em>a shocking device</em>...</td>
</tr>
<tr>
<td>Beneficiary</td>
<td>Whenever Ann makes hotel reservations for <em>her boss</em>...</td>
</tr>
<tr>
<td>Source</td>
<td>I flew in from <em>Boston</em>.</td>
</tr>
<tr>
<td>Goal</td>
<td>I drove to <em>Portland</em>.</td>
</tr>
</tbody>
</table>
Thematic roles

<table>
<thead>
<tr>
<th>Role</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agent</td>
<td>The volitional causer of an event</td>
</tr>
<tr>
<td>Experiencer</td>
<td>The experiencer of an event</td>
</tr>
<tr>
<td>Force</td>
<td>The non-volitional causer of the event</td>
</tr>
<tr>
<td>Theme</td>
<td>The participant most directly affected by an event</td>
</tr>
<tr>
<td>Result</td>
<td>The end product of an event</td>
</tr>
<tr>
<td>Content</td>
<td>The proposition or content of a propositional event</td>
</tr>
<tr>
<td>Instrument</td>
<td>An instrument used in an event</td>
</tr>
<tr>
<td>Beneficiary</td>
<td>The beneficiary of an event</td>
</tr>
<tr>
<td>Source</td>
<td>The origin of the object of a transfer event</td>
</tr>
<tr>
<td>Goal</td>
<td>The destination of an object of a transfer event</td>
</tr>
</tbody>
</table>

- John broke the window
- The window was broken by John
- John broke the window with a rock
- The rock broke the window
- The window broke
Thematic roles

The thematic roles for verbs generally are predictable by the syntactic position of the argument (specific to each verb class). Some allow for consistent alternations:

Doris gave the book to Cary

Doris gave Cary the book
Thematic roles

• Thematic roles are very useful but difficult to formally define AGENT, THEME, etc.

• At the same time, they may be too coarse for some applications.
Thematic roles

- The cook opened the jar with the new gadget
- The new gadget opened the jar
- Shelly ate the sliced banana with a fork
- *The fork ate the sliced banana

Intermediary instruments can be subjects

Enabling instruments cannot

Levin and Rappaport Hovav 2005; SLP3
Coarsening: Proto-roles

- Proto-roles = generalized thematic roles
- Proto-agent: causing an event, having volition wrt event, moving, acting with intention
- Proto-patient: change of state, causally affected by event
• Sentences from the Penn Treebank annotated with proto-roles, along with lexical entries for each sense of a verb identifying the specific meaning of each proto-role for that verb sense.
(22.11) **agree.01**

Arg0: Agreer
Arg1: Proposition
Arg2: Other entity agreeing

Ex1:  [Arg0 The group] *agreed* [Arg1 it wouldn’t make an offer].
Ex2:  [ArgM-TMP Usually] [Arg0 John] *agrees* [Arg2 with Mary] [Arg1 on everything].

(22.12) **fall.01**

Arg1: Logical subject, patient, thing falling
Arg2: Extent, amount fallen
Arg3: start point
Arg4: end point, end state of arg1

Ex1:  [Arg1 Sales] *fell* [Arg4 to $25 million] [Arg3 from $27 million].
Ex2:  [Arg1 The average junk bond] *fell* [Arg2 by 4.2%].
Verb-specific argument structures lets us map the commonalities among the different surface forms

• \([\text{Arg}_0 \text{ Big Fruit Co. }]\) increased \([\text{Arg}_1 \text{ the price of bananas}]\).

• \([\text{Arg}_1 \text{ The price of bananas}]\) was increased again \([\text{Arg}_0 \text{ by Big Fruit Co. }]\).

• \([\text{Arg}_1 \text{ The price of bananas}]\) increased \([\text{Arg}_2 \text{ 5%}]\).
Verb-specific argument structures lets us map the commonalities among the different surface forms

• \([\text{Arg}_0 \text{ Big Fruit Co. }]\) increased \([\text{Arg}_1 \text{ the price of bananas}]\).

• \([\text{Arg}_1 \text{ The price of bananas}]\) was increased again \([\text{Arg}_0 \text{ by Big Fruit Co. }]\).

• \([\text{Arg}_1 \text{ The price of bananas}]\) increased \([\text{Arg}_2 5\%]\).
• [Arg1 The price of bananas] increased [Arg2 5%].
• [Arg1 The price of bananas] rose [Arg2 5%].
• There has been a [Arg2 5%] rise [Arg1 in the price of bananas].
FrameNet

- Propbank maps argument structure for individual verb senses
- FrameNet maps argument structure for frames, which are evoked by a lexical unit (typically a verb)

https://framenet.icsi.berkeley.edu/fndrupal/framenet_data
Frames

AI
- Schank and Abelson 1975, 1977
- Minsky 1974

Cognitive Psychology
- Rumelhart 1975, 1980

Linguistics
- Fillmore 1975, 1982, Tannen 1979

Sociology
- Goffman 1975

Media Studies
- Entman 1993
Frames

John went into a restaurant. He ordered a hamburger and coke. He asked the waitress for the check and left.

(Schank & Abelson 75)
Frames

• “A frame is a data-structure for representing a stereotyped situation” (Minsky 1975)

• By the term ‘frame’ I have in mind any system of concepts related in such a way that to understand any one of them you have to understand the whole structure in which it fits; when one of the things in such a structured is introduced … all of the others are automatically made available.” (Fillmore 1982)
Who did what to whom?

- John *bought* the car at the dealership
- The car was *bought* by John
- John’s *purchase* of the car
- The *sale* of the car cleared their inventory.
Who did what to whom?

- John bought the car at the dealership
- The car was bought by John
- John’s purchase of the car
- The sale of the car cleared their inventory.
Who did what to whom?

- John bought the car at the dealership
- The car was bought by John
- John’s purchase of the car
- The sale of the car cleared their inventory.
Semantic Frame

**Apply_heat**

- **Lexical units:**
  
  bake.v, barbecue.v, blanch.v, boil.v, braise.v, broil.v, brown.v, char.v, coddle.v, cook.v, deep fry.v, fry.v, grill.v, microwave.v, parboil.v, plank.v, poach.v, roast.v, saute.v, scald.v, sear.v, simmer.v, singe.v, steam.v, steep.v, stew.v, toast.v

- **Core Frame Elements:**

<table>
<thead>
<tr>
<th>Cook</th>
<th>The Cook applies heat to the Food.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food</td>
<td>Food is the entity to which heat is applied by the Cook.</td>
</tr>
<tr>
<td>Heating instrument</td>
<td>The entity that directly supplies heat to the Food.</td>
</tr>
<tr>
<td>Container</td>
<td>The Container holds the Food to which heat is applied.</td>
</tr>
<tr>
<td>Temperature setting</td>
<td>The Temperature_setting of the Heating_instrument for the Food.</td>
</tr>
</tbody>
</table>
Semantic Frame

DESTROY

• Lexical units:

annihilate.v, annihilation.n, blast.v, blow up.v, demolish.v, demolition.n, destroy.v, destruction.n, destructive.a, devastate.v, devastation.n, dismantle.v, dismantlement.n, lay waste.v, level.v, obliterate.v, obliteration.n, raze.v, ruin.v, take out.v, unmake.v, vaporize.v

• Core Frame Elements:

<table>
<thead>
<tr>
<th>Cause</th>
<th>The event or entity which is responsible for the destruction of the Patient.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Destroyer</td>
<td>The conscious entity, generally a person, that performs the intentional action that results in the Patient’s destruction.</td>
</tr>
<tr>
<td>Patient</td>
<td>The entity which is destroyed by the Destroyer.</td>
</tr>
</tbody>
</table>
Semantic representations

Two different perspectives on a commercial transaction
Multilingual frames

I bought a car from you.

BUYER

GOODS

SELLER

Sie verkauft mir ein Auto.

SB

DA

NK

OA
Multilingual frames

- French
- Chinese
- Brazilian Portuguese
- German
- Spanish
- Japanese
- Swedish
- Korean

https://framenet.icsi.berkeley.edu/fndrupal/framenets_in_other_languages
Semantic role labeling

• Input: a sentence

• Output:

  • A list of predicates, each containing:

    • a label (e.g., Framenet frame)
    • a span
    • a set of arguments, each containing:

      • a label (thematic role, FrameNet role)
      • a span

Smith 2017
Semantic role labeling

FrameNet

[You] can’t [blame] [the program] [for being unable to identify it]
COGNIZER TARGET EVLUEE REASON

PropBank

[The San Francisco Examiner] issued [a special edition] [yesterday]
ARG0 TARGET ARG1 ARGM-TMP

How would we do this?
Semantic role labeling

function SEMANTICROLELABEL(words) returns labeled tree

parse ← PARSE(words)
for each predicate in parse do
    for each node in parse do
        featurevector ← EXTRACTFEATURES(node, predicate, parse)
        CLASSIFYNODE(node, featurevector, parse)
Semantic role labeling

Predicate: shot
Phrase type = NP
Headword of phrase = elephant
Path = NP↑S↓VP
Voice of verb = active
Voice of verb = passive
Phrase before verb?
First/last words of phrase
Semantic role labeling

Collobert et al. (2011), Natural Language Processing (Almost) from Scratch
Semantic role labeling

• Sentence-level constraints:
  • Arguments can’t overlap
  • For a given predicate, typically only one argument of each type (e.g., ARG0, BUYER)

• Approximate joint decoding (Das et al. 2010)
• Constrained optimization (e.g., ILP)
Data

- PropBank
  https://propbank.github.io

- FrameNet
  https://framenet.icsi.berkeley.edu/fndrupal/framenet_data