Introduction to semantic parsing

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Full understanding?

• We’re doing natural language understanding, right?

• Are we there yet? Do we fully understand?
  ◦ With VSMs? Sentiment analysis? Relation extraction?
  ◦ Arguably, all are steps toward NLU … but are they sufficient?

• How to generate complete, precise semantics?
  ◦ “Barack and Michelle Obama got married in 1992 in Chicago.”
  ◦ “No one may enter the building except policemen or firefighters.”
Six sculptures — C, D, E, F, G, H — are to be exhibited in rooms 1, 2, and 3 of an art gallery.

- Sculptures C and E may not be exhibited in the same room.
- Sculptures D and G must be exhibited in the same room.
- If sculptures E and F are exhibited in the same room, no other sculpture may be exhibited in that room.
- At least one sculpture must be exhibited in each room, and no more than three sculptures may be exhibited in any room.

If sculpture D is exhibited in room 3 and sculptures E and F are exhibited in room 1, which of the following may be true?

A. Sculpture C is exhibited in room 1.
B. Sculpture H is exhibited in room 1.
C. Sculpture G is exhibited in room 2.
D. Sculptures C and H are exhibited in the same room.
E. Sculptures G and F are exhibited in the same room.
Challenge: anaphoric adjectives

“Sculptures D and G must be exhibited in the same room.”

(if (and (in D X) (in G Y)) (= X Y))

“Sculptures D and G must be exhibited in the red room.”

(if (and (in D X) (in G Y)) (and (red X) (red Y)))

“Sculptures D and G must be exhibited in the large room.”

(if (and (in D X) (in G Y)) (and (large X) (large Y)))

“Sculptures D and G must be exhibited in the smelly room.”

(if (and (in D X) (in G Y)) (and (smelly X) (smelly Y)))
Challenge: scope ambiguity

In this country a woman gives birth every 15 minutes. Our job is to find that woman, and stop her.
— Groucho Marx
Challenge: scope ambiguity

"No more than three sculptures may be exhibited in any room."

There cannot be a room that contains more than three sculptures.

No more than three sculptures may be exhibited at all — no matter what room.

At most three sculptures have the property that they may be exhibited in any room. (For other sculptures, there are restrictions on allowable rooms.)
Travel reservations

Yes, hi, I need to book a flight for myself and my husband from SFO to Boston. Actually Oakland would be OK too. We need to fly out on Friday the 12th, and then I could come back on Sunday evening or Monday morning, but he won’t return until Wednesday the 18th, because he’s staying for business. No flights with more than one stop, and we don’t want to fly on United because we hate their guts.
SHRDLU (Winograd 1972)

Find a block which is taller than the one you are holding and put it into the box.

OK.

How many blocks are not in the box?

FOUR OF THEM.

Is at least one of them narrower than the one which I told you to pick up?

YES, THE RED CUBE.

http://youtube.com/watch?v=8SvD-lNg0TA
http://hci.stanford.edu/winograd/shrdlu/
CHAT-80

- Developed 1979-82 by Fernando Pereira & David Warren
- Proof-of-concept natural language interface to database
- Could answer questions about geography
- Implemented in Prolog
- Hand-built lexicon & grammar
- Highly influential NLIDB system
CHAT-80 demo

You can run Chat-80 yourself on the rice machines!

$ ssh rice.stanford.edu
$ cd /afs/ir/class/cs224u/chat-80/
$ module load sicstus
$ sicstus
? [load].
? hi.
? what is the capital of france?

Sample queries can be found at:

/afs/ir/class/cs224u/chat-80/demo

All the source code is there for your perusal as well.
Things you could ask CHAT-80

• Is there more than one country in each continent?
• What countries border Denmark?
• What are the countries from which a river flows into the Black_Sea?
• What is the total area of countries south of the Equator and not in Australasia?
• Which country bordering the Mediterranean borders a country that is bordered by a country whose population exceeds the population of India?
• How far is London from Paris?
The CHAT-80 database

% Facts about countries.
% country(Country, Region, Latitude, Longitude,
%   Area(sqmiles), Population, Capital, Currency)
country(andorra, southern_europe, 42, -1, 179, 25000,
andorra_la_villa, franc_peseta).
country(angola, southern_africa, -12, -18, 481351, 5810000, luanda,
?).
country(argentina, south_america, -35, 66, 1072067, 23920000,
buenos_aires, peso).

capital(C,Cap) :- country(C,__,__,____,___,Cap,__).
The CHAT-80 grammar

/* Sentences */
sentence(S) --> declarative(S), terminator(.) .
sentence(S) --> wh_question(S), terminator(?) .
sentence(S) --> yn_question(S), terminator(?) .
sentence(S) --> imperative(S), terminator(!) .

/* Noun Phrase */
np(np(Agmt,Pronoun,[]),Agmt,NPCase,def,_,Set,Nil) -->
  {is_pp(Set)},
  pers_pron(Pronoun,Agmt,Case),
  {empty(Nil), role(Case,decl,NPCase)}.

/* Prepositional Phrase */
pp(pp(Prep,Arg),Case,Set,Mask) -->
  prep(Prep),
  {prep_case(NPCase)},
  np(Arg,_,NPCase,_,Case,Set,Mask).
Precision vs. robustness

<table>
<thead>
<tr>
<th>Precise, complete understanding</th>
<th>Brittle, narrow coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuzzy, partial understanding</td>
<td>Robust, broad coverage</td>
</tr>
</tbody>
</table>

SHRDLU  CHAT-80
Carbon emissions

Which country has the highest CO2 emissions?
What about highest per capita?
Which had the biggest increase over the last five years?
What fraction was from European countries?
Baseball statistics

Pitchers who have struck out four batters in one inning
Players who have stolen at least 100 bases in a season
Complete games with fewer than 90 pitches
Most home runs hit in one game
Voice commands

How do I get to the Ferry Building by bike
Book a table for four at Nopa on Friday after 9pm
Text my wife I’m going to be twenty minutes late
Add Altered Carbon to my Netflix queue at the top
Semantic parsing

If we want to understand natural language completely and precisely, we need to do semantic parsing.

That is, translate natural language into a formal meaning representation on which a machine can act.

First, we need to define our goal.

What should we choose as our target output representation of meaning?
Database queries

To facilitate data exploration and analysis, you might want to parse natural language into database queries:

*which country had the highest carbon emissions last year*

```
SELECT country.name
FROM country, co2_emissions
WHERE country.id = co2_emissions.country_id
AND co2_emissions.year = 2014
ORDER BY co2_emissions.volume DESC
LIMIT 1;
```
Robot control

For a robot control application, you might want a custom-designed procedural language:

*Go to the third junction and take a left.*

```
(do-sequentially
 (do-n-times 3
   (do-sequentially
     (move-to forward-loc)
     (do-until
       (junction current-loc)
       (move-to forward-loc)))
   (turn-left))}
```
## Intents and arguments

For smartphone voice commands, you might want relatively simple meaning representations, with *intents* and *arguments*:

<table>
<thead>
<tr>
<th>Intent</th>
<th>Argument</th>
</tr>
</thead>
</table>
| *directions to SF by train* | (TravelQuery  
  (Destination /m/0d6lp)  
  (Mode TRANSIT)) |
| *text my wife on my way* | (SendMessage  
  (Recipient 0x31cbf492)  
  (MessageType SMS)  
  (Subject "on my way")) |
| *angelina jolie net worth* | (FactoidQuery  
  (Entity /m/0f4vbz)  
  (Attribute /person/net_worth)) |
| *play sunny by boney m* | (PlayMedia  
  (MediaType MUSIC)  
  (SongTitle "sunny")  
  (MusicArtist /m/017mh)) |
| *weather friday austin tx* | (WeatherQuery  
  (Location /m/0vzm)  
  (Date 2019-05-10)) |
| *is REI open on sunday* | (LocalQuery  
  (QueryType OPENING_HOURS)  
  (Location /m/02nx4d)  
  (Date 2019-05-12)) |
Semantic parsing vs. machine translation

• Both involve translating from one semantic representation into another.
• Both involve complex structures, often related in complex ways.
• Some techniques are transferable: co-occurrence analysis, alignment, ...
• But in machine translation, the target semantic representation is not machine-readable! Rather, it is human-readable.

(TravelQuery (Destination /m/0d6lp) (Mode TRANSIT))

<table>
<thead>
<tr>
<th>directions</th>
<th>to</th>
<th>SF</th>
<th>by</th>
<th>train</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Wegbeschreibung</th>
<th>nach</th>
<th>SF</th>
<th>mit</th>
<th>dem Zug</th>
</tr>
</thead>
</table>
SippyCup

SippyCup is a simple semantic parser, written in Python, created purely for didactic purposes.

The design favors simplicity and readability over efficiency and performance.

The goal is to make semantic parsing look easy!
SippyCup units

Unit 0  Introduction to semantic parsing

Unit 1  Natural language arithmetic
       “two times three plus four”

Unit 2  Travel queries
       “driving directions to williamsburg virginia”

Unit 3  Geographical queries
       “how many states border the largest state”
Outline of an approach

- Similar to much recent academic work in semantic parsing
  - Luke Zettlemoyer, Percy Liang, and many others
- Define possible syntactic structures using a context-free grammar
- Construct semantics bottom-up, following syntactic structure
- Score parses with a log-linear model learned from training data
- Leverage annotators for names, numbers, places, times, ...
- Use grammar induction to avoid manual grammar engineering
Context-free grammar

The *syntactic* part of the grammar is a fairly conventional CFG:

\[
\begin{align*}
    \text{Loc} & \rightarrow \text{Google} \\
    \text{Loc} & \rightarrow \text{NY} \\
    \text{Loc} & \rightarrow \text{Loc in Loc} \\
    \text{Opt} & \rightarrow \text{me} \\
    \text{Mode} & \rightarrow \text{bike} \\
    \text{Mode} & \rightarrow \text{car} \\
    \text{ROOT} & \rightarrow \text{route (Opt)? to Loc by Mode}
\end{align*}
\]

Usually *not* deterministic: many possible derivations per input.
Example parse

route me to Google in NY by bike
Parsing algorithm

• An adaptation of the CYK chart parsing algorithm
  ○ (A nice example of dynamic programming)
• Rewrite the grammar so that all rules are binary (or unary)
• Consider every span of tokens in input, bottom-up
• Consider all ways of splitting span into two sub-spans
• Consider all grammar rules whose RHSes match the sub-spans
• Record the categories (LHSes) we can construct for the span
Semantic attachments to CFG rules

Little programs which compute semantic interpretation bottom-up

$\text{Loc} \rightarrow \text{Google} \ [\text{/m/045c7b}]$
$\text{Loc} \rightarrow \text{NY} \ [\text{/m/02_286}]$
$\text{Loc} \rightarrow \text{Loc in Loc} \ [(\text{In } 1 \ 2)]$
$\text{Opt} \rightarrow \text{me} \ []$
$\text{Mode} \rightarrow \text{bike} \ [\text{BIKE}]$
$\text{Mode} \rightarrow \text{car} \ [\text{CAR}]$
$\text{ROOT} \rightarrow \text{route} (\text{Opt})? \ \text{to} \ \text{Loc} \ \text{by} \ \text{Mode}$

\[ [(\text{GetDirections (Destination } 2) (\text{Mode } 3))] \]
Example parse, now with semantics!

(GetDirections (Destination (In /m/045c7b /m/02_286)) (Mode BIKE))

$ROOT

$(In /m/045c7b /m/02_286)

$Loc

$(/m/045c7b $Loc /m/02_286 $Mode)

$Opt

route me to Google in NY by bike
Annotators

- Don’t want a million rules like: $\text{Loc} \rightarrow \text{NY} \quad [/m/02_{286}]$
- Instead, leverage intelligence of special-purpose annotators

<table>
<thead>
<tr>
<th>$\text{Restaurant}$</th>
<th>$\text{Contact}$</th>
<th>$\text{Date}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FreebaseAnnotator</td>
<td>ContactAnnotator</td>
<td>DateAnnotator</td>
</tr>
<tr>
<td>entity: /m/01zn1l</td>
<td>uid: 0x392a14bc</td>
<td>date: 2019-05-10</td>
</tr>
<tr>
<td>collections:</td>
<td>email: <a href="mailto:tomg@gmail.com">tomg@gmail.com</a></td>
<td></td>
</tr>
<tr>
<td>/dining/restaurant,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>/business/location</td>
<td></td>
<td></td>
</tr>
<tr>
<td>confidence: 0.812</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

reserve  gary  danko  with  tom  next  friday
When grammar supports multiple interpretations, how to choose?

(GetDirections
 (Destination /m/02ll7r)
 (Mode BIKE))

(GetDirections
 (Destination /g/1tfmcmgjy))
Scoring model

- A log-linear model to score alternative derivations (parses)
- Features from input $x$, semantic yield $y$, and derivation $z$
  - E.g., co-occurrence of “to” in input and Destination in semantics
  - E.g., occurrence of specific CFG rules or categories in derivation
  - E.g., confidence score from an annotator

\[
\text{score}(x, z) = \text{features}(x, z)^\top \theta
\]

\[
p(z|x, \theta) = \frac{e^{\text{score}(x, z)}}{\sum_{z' \in Z(x)} e^{\text{score}(x, z')}}
\]
Learning

• Estimate parameters using EM-style training (Liang et al., 2011)
• Assume we have training data \((x_1, y_1), \ldots, (x_n, y_n)\)
• Sum out latent derivations in n-best list

\[
\arg\max_{\theta} \sum_z p(y|z) p(z|x, \theta)
\]

• Update using Stochastic Gradient Descent (SGD)
Grammar induction

- Next: where do the grammar rules come from?
- For small domains, we can write the rules manually
- But for large, complex domains, this doesn’t scale!
- Want to *induce* rules automatically from training data
- One strategy: reduce grammar induction to learning
  - Generate *all* possible rules (given all possible words, semantics)
  - Then use standard learning methods to train rule weights
  - But, exponential blowup $\Rightarrow$ requires pruning strategies
Data

- Of course, the whole enterprise depends upon having data
- Ideally, *lots* of data — as usual, more data trumps cleverer models
- Problem: examples annotated with semantics are expensive
- Solution: learn from indirect supervision, using the results of *evaluating* the semantics (e.g., learning from denotations)
Recap

We map queries into structured representations of meaning using:

- Context-free grammars with semantic attachments
- Log-linear scoring models, with weights learned from data
- Leverage annotators for entities, contacts, dates, …
- Methods for inducing grammar rules from data
- Lots and lots and lots of data!