Computational Semantics

CS224N
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(Borrows some slides from Mary Dalrymple, Jason Eisner, and Jim Martin)

Why study computational semantics?

- Because everyone has been wanting to hear about this all course?!?
- Obvious high-level applications
  - Question answering
  - Information access
  - Talking to your pet robot
  - Speech user interfaces
  - Summarization
  - Translation
- The next generation of intelligent applications need deeper semantics than we have seen so far
  - Often you must understand well to be able to act

Shallow vs. deep semantics

We can do more than people thought without deep linguistic analysis

This is ***the*** lesson of the last decade

Shallow vs. deep semantics

But we can't do everything we would like

Shallow vs. deep semantics

We can't do everything we would like:

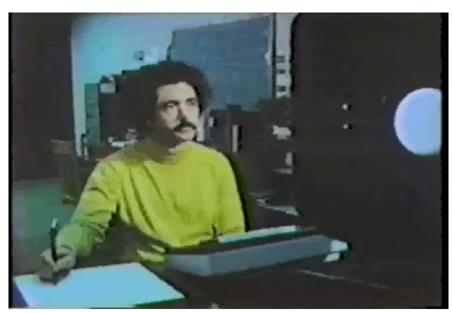
- Not all tasks can ignore language structure/meaning
- Unsuitable if new text must be generated
- Unsuitable if machine must act rather than relying on user to interpret material written by the author of the document

You get what you pay for:

- Cheap, fast, low-level techniques are appropriate when speed and volume are more important than accuracy
- Computationally expensive, higher-level techniques are appropriate when high-quality results are required

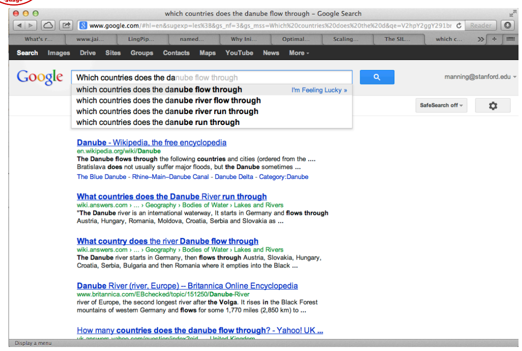
SHRDLU

http://hci.stanford.edu/winograd/shrdlu/

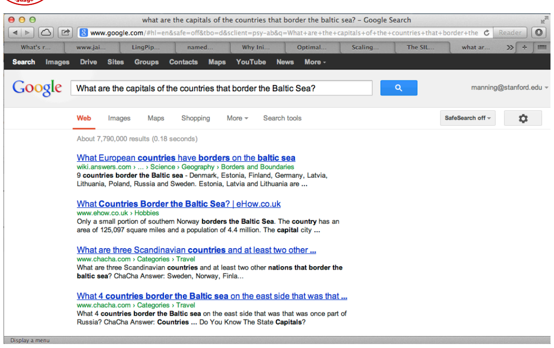


Google: What is the capital of Algeria?

Google: Which countries does the Danube flow through?



Google: What are the capitals of the countries bordering the Baltic Sea?



Apple Knowledge Navigator video (1987)

Precise semantics. An early example: Chat-80

- Developed between 1979 and 1982 by Fernando Pereira and David Warren; became Pereira's dissertation
- Proof-of-concept natural language interface to database system
- Used in projects: e.g. Shoptalk (Cohen et al. 1989), a natural language and graphical interface for decision support in manufacturing
- Used in an AppliedNLP-2000 conference paper! [Asking about train routes and schedules – still live]
- Available in /afs/ir/class/cs224n/src/chat
  - UNFORTUNATELY THERE DOESN'T SEEM TO BE ANY PROLOG INTERPRETER ON ITS MACHINES NOW ☹

Things you could ask…

- What is the total area of countries south of the Equator and not in Australasia?
- What is the average area of the countries in each continent?
- Is there more than one country in each continent?
- What are the countries from which a river flows into the Black_Sea?
- Which country bordering the Mediterranean borders a country that is bordered by a country whose population exceeds the population of India?

Chat-80 trace (small)

```
Question: What is the capital of
    Australia?
Parse: 0.0sec.
whq
  $VAR
    1
  s
    np
      3+sin
      wh(B)
      []
    verb(be,active,pres+fin,[],pos)
    arg
      dir
      np
        3+sin
        np_head
          det(the(sin))
          []
          capital
        pp
          prep(of)
          np
            3+sin
            name(australia)
            []
      []

Semantics: 0.0sec.
answer([B]) :-
   capital(australia,B)

canberra.
```

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).
```

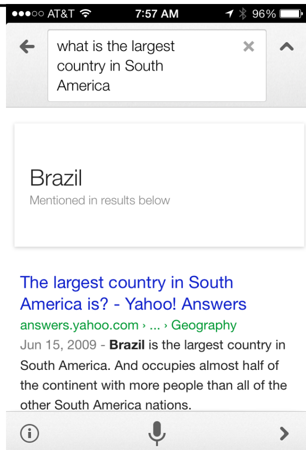
Fast-forward to 2015

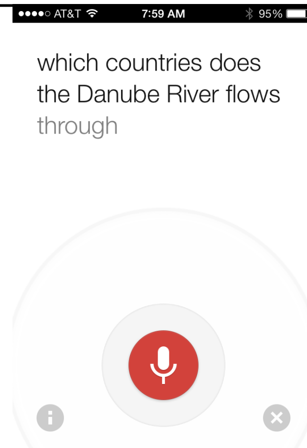
- Siri
- Google Now
- Cortana
- Amazon Echo / Alexa
- Nuance Nina
- Facebook M

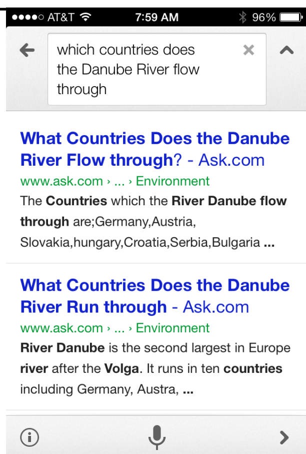
Speech is fast becoming the preferred mobile UI

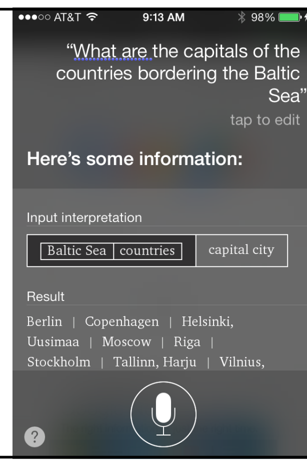
- Satya Nadella (MSFT), NEXT Economy conference, Nov '15: "speaking and texting will be 'the new U.I.' for software."

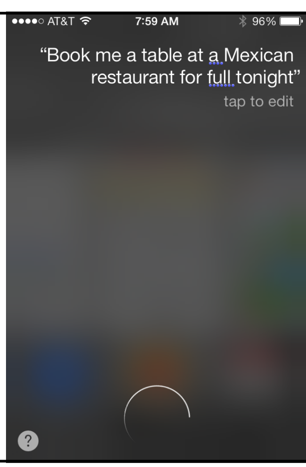
Natural Language Understanding becomes necessary

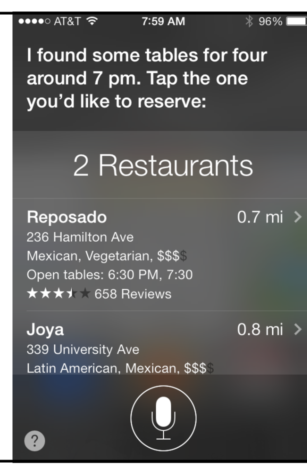

●●●○○ AT&T 7:57 AM 96%
what is the largest country in South America
Brazil
Mentioned in results below
The largest country in South America is? - Yahoo! Answers
answers.yahoo.com › ... › Geography
Jun 15, 2009 - Brazil is the largest country in South America. And occupies almost half of the continent with more people than all of the other South America nations.


●●●●○ AT&T 7:59 AM 95%
which countries does the Danube River flows through


●●●●○ AT&T 7:59 AM 96%
which countries does the Danube River flow through
What Countries Does the Danube River Flow through? - Ask.com
www.ask.com › ... › Environment
The Countries which the River Danube flow through are;Germany,Austria, Slovakia,hungary,Croatia,Serbia,Bulgaria ...
What Countries Does the Danube River Run through - Ask.com
www.ask.com › ... › Environment
River Danube is the second largest in Europe river after the Volga. It runs in ten countries including Germany, Austra, ...


●●●●○ AT&T 9:13 AM 98%
“What are the capitals of the countries bordering the Baltic Sea”
tap to edit
Here’s some information:
Input interpretation
Baltic Sea | countries | capital city
Result
Berlin | Copenhagen | Helsinki, Uusimaa | Moscow | Riga | Stockholm | Tallinn, Harju | Vilnius,


●●●●○ AT&T 7:59 AM 96%
“Book me a table at a Mexican restaurant for full tonight”
tap to edit


●●●●○ AT&T 7:59 AM 96%
I found some tables for four around 7 pm. Tap the one you’d like to reserve:
2 Restaurants
Reposado 0.7 mi
236 Hamilton Ave
Mexican, Vegetarian, $$$$
Open tables: 6:30 PM, 7:30
658 Reviews
Joya 0.8 mi
339 University Ave
Latin American, Mexican, $$$$

Google's latest – Nov 16, 2015

http://insidesearch.blogspot.com/2015/11/the-google-app-now-understands-you.html

The Google app can now handle superlatives

"*Who are the tallest Mavericks players?*"

Second, we now understand questions with dates:

"*What songs did Taylor Swift record in 2014?*"

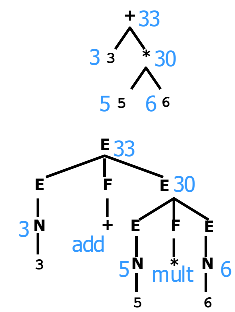
Finally, we're starting to understand some complex combinations:

"*What are some of Seth Gabel's father-in-law's movies?*"

"*What was the U.S. population when Bernie Sanders was born?*"

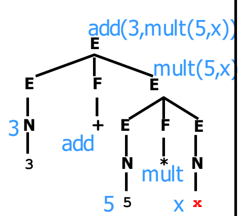
Programming Language Interpreter

- What is meaning of 3+5*6?
- First parse it into 3+(5*6)
- Now give a meaning to each node in the tree (bottom-up)



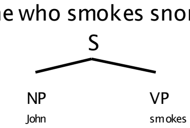
More complex meanings

- How about 3+5*x?
- Don't know x at compile time
- "Meaning" at a node is a piece of code, not a number
- Form is "rule-to-rule" translation
  - We provide a way to form the semantics of each parent in terms of the semantics of the children



(Formal/Compositional) Computational Semantics

- Sentences: "John smokes."
  "Everyone who smokes snores."
- Syntactic Analyses:



- Semantics Construction: smoke(j)
  - Logic as meaning representation language
- Inference: ∀x.smoke(x)→snore(x), smoke(j)
  => snore(j)

Logic: Some Preliminaries

Three major kinds of objects

1. Booleans (Bool)
   - Roughly, the semantic values of sentences
2. Individuals/Entities (Ind)
   - Values of NPs, i.e., objects
   - Maybe also other types of entities, like times
3. Functions of various types
   - A function returning a boolean is called a "predicate"
     - e.g., frog(x), green(x)
     - A predicate defines a set of individuals that satisfy it
     - A one argument predicate is called a "property"
   - More complex functions return other functions!
   - Some functions take other functions as arguments!
     - (Higher order functions.)

Logic: Lambda Terms

- Lambda terms:
  - Let square = λp p*p
  - Then square(3) = (λp p*p)(3) = 3*3
  - Note: square(x) isn't a function! It's just the value x*x.
  - But **λx** square(x) = λx x*x = λp p*p = square
    (proving that these functions are equal – and indeed they are, as they act the same on all arguments: what is (λx square(x))(y)?)
  - Let even = λp (p mod 2 == 0) a <u>predicate:</u> returns true/false
  - even(x) is true if x is even
  - How about even(square(x))?
  - λx even(square(x)) is true of numbers with even squares
    - Just apply rules to get λx (even(x*x)) = λx (x*x mod 2 == 0)
    - This happens to denote the same predicate as even does

Logic: Multiple Arguments

- All lambda terms have one argument
- But we can fake multiple arguments ...

- Suppose we want to write times(5,6)
- Remember: square can be written as λx.square(x)
- Similarly, times is equivalent to λx.[λy.times(x,y)]

- Claim that times(5)(6) means same as times(5,6)
  - times(5) = (λx.λy.times(x,y)) (5) = λy.times(5,y)
    - If this function weren't anonymous, what would we call it?
  - times(5)(6) = (λy times(5,y))(6) = times(5,6)
- Referred to as "currying"

Logic: Interesting Constants

- We have "constants" that name some of the entities and functions (e.g., times):
  - GeorgeWBush – an entity
  - red – a predicate on entities
    - holds of just the red entities: red(x) is true if x is red!
  - loves – a predicate on 2 entities
    - loves(GeorgeWBush, LauraBush)
    - *Question:* What does loves(LauraBush) denote?
- Constants used to define meanings of words
- Meanings of phrases will be built from the constants

Compositional Semantics

- We've discussed what semantic representations should look like.
- **But how do we get them from sentences???**
- First - parse to get a syntax tree.
- Second - look up the semantics for each word.
- Third - build the semantics for each constituent
  - Work from the bottom up
  - The syntax tree is a "recipe" for how to do it
- Principle of Compositionality
  - The meaning of a whole is derived from the meanings of the parts, via composition rules

A simple grammar of English
(in Definite Clause Grammar, DCG, form – as in Prolog)

sentence --> noun_phrase, verb_phrase.
noun_phrase --> proper_noun.
noun_phrase --> determiner, noun.
verb_phrase --> verb, noun_phrase.

Proper_noun --> [John]	verb --> [ate]
Proper_noun --> [Mary]	verb --> [kissed]
determiner --> [the]	noun --> [cake]
determiner--> [a]	noun --> [lion]

Extending the grammar to check number agreement between subjects and verbs

S --> NP(Num), VP(Num).
NP(Num) --> proper_noun(Num).
NP(Num) --> det(Num), noun(Num).
VP(Num) --> verb(Num), NP(_).

proper_noun(s) --> [Mary].	noun(s) --> [lion].
det(s) --> [the].	noun(p) --> [lions].
det(p) --> [the].	verb(s) --> [eats].
	verb(p) --> [eat].

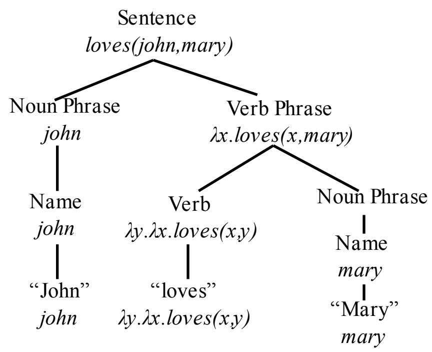
A simple DCG grammar with semantics

sentence(SMeaning) --> noun_phrase(NPMeaning), verb_phrase(VPMeaning), {combine (NPMeaning, VPMeaning, SMeaning)}.
verb_phrase(VPMeaning) --> verb(Vmeaning), noun_phrase(NPMeaning), {combine (NPMeaning, VMeaning, VPMeaning)}.
noun_phrase (NPMeaning) --> name(NPMeaning).

name(john) --> [john].	verb(λx.jumps(x)) --> [jumps]
name(mary) --> [mary].	verb(λy.λx.loves(x,y)) -->[loves]

Combine(X, Y, Z) --> apply(Y, X, Z)

Parse tree with associated semantics



In detail: Beta-Reduction

(λyλx.love(x,y)[mary][john]
β=> (λx.love(x,mary))[john]
β=> love(john,mary)

Formal Compositional Semantics …

- **Richard Montague** (1930-1971)
- *"… I reject the contention that an important theoretical difference exists between formal and natural languages …"*

Augmented CFG Rules

- We can also accomplish this just by attaching semantic formation rules to our syntactic CFG rules

$$A \rightarrow \alpha_1 \ldots \alpha_n \qquad \{f(\alpha_1.sem, \ldots, \alpha_n.sem)\}$$

- This should be read as the semantics we attach to A can be computed from some function applied to the semantics of A's parts.
- The functions/operations in the semantic rules can be restricted, falling into two classes
  - Pass the semantics of a daughter up unchanged to the mother
  - Apply (as a function) the semantics of one of the daughters of a node to the semantics of the other daughters

How do things get more complex? (The former) GRE analytic section

- 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?
  1. Sculpture C is exhibited in room 1.
  2. Sculpture H is exhibited in room 1.
  3. Sculpture G is exhibited in room 2.
  4. Sculptures C and H are exhibited in the same room.
  5. Sculptures G and F are exhibited in the same room.

Logic: Interesting Constants

- Generalized Quantifiers
- most – a predicate on 2 predicates on entities
  - most(pig, big) = "most pigs are big"
    - Equivalently, most(λx pig(x), λx big(x))
  - returns true if most of the things satisfying the first predicate also satisfy the second predicate
- similarly for other quantifiers
  - all(pig,big) (equivalent to ∀x pig(x) ⇒ big(x))
  - exists(pig,big) (equivalent to ∃x pig(x) AND big(x))
  - can even build complex quantifiers from English phrases:
    - "between 12 and 75"; "a majority of"; "all but the smallest 2"

Quantifier Order

- Groucho Marx celebrates quantifier order ambiguity:
  - `In this country` <u>`a woman`</u> `gives birth` <u>`every 15 min`</u>`.`
    `Our job is to find that woman and stop her.`
  - ∃woman (∀15min gives-birth-during(woman, 15min))
  - ∀15min (∃woman gives-birth-during(15min, woman))
  - Surprisingly, both are possible in natural language!
  - Which is the joke meaning?
    - (where it's always the same woman)

Scope Needs to be Resolved!

At least one sculpture must be exhibited in each room.
The same sculpture in each room?
No more than three sculptures may be exhibited in any room.
Reading 1: For every room, there are no more than three sculptures exhibited in it.
Reading 2: Only three or less sculptures are exhibited (the rest are not shown).
Reading 3: Only a certain set of three or less sculptures may be exhibited in any room (for the other sculptures there are restrictions in allowable rooms).

- Some readings will be ruled out by being uninformative or by contradicting other statements
- Otherwise we must be content with distributions over scope-resolved semantic forms

An alternative: Semantic Grammars

- A problem with traditional linguistic grammars is that they don't necessarily reflect the semantics in a straightforward way
- You can deal with this by...
  - Fighting with the grammar
    - Complex lambdas and complex terms, etc.
  - Rewriting the grammar to reflect the semantics
    - And in the process give up on some syntactic niceties
    - known as "Semantic grammars"
      - Simple idea, dumb name

Lifer Semantic Grammars

- Example domain—access to DB of US Navy ships
  S → <present> the <attribute> of <ship>
  <present> → what is | [can you] tell me
  <attribute> → length | beam | class
  <ship> → the <shipname>
  <shipname> → kennedy | enterprise
  <ship> → <classname> class ships
  <classname> → kitty hawk | lafayette
- Example inputs recognized by above grammar:
  can you tell me the class of the Enterprise
  what is the length of Kitty Hawk class ships
  - Many categories are not "true" syntactic categories
  - Words are recognized by their context rather than category (e.g. *class*)
  - Recognition is strongly directed
  - Strong direction useful for error detection and correction
    - G. Hendrix, E. Sacerdoti, D. Sagalowicz, and J.Slocum. 1978. Developing a natural language interface to complex data. ACM Transactions on Database Systems 3:105-147

Semantic Grammar

- The term semantic grammar refers to the motivation for the grammar rules
  - The technology (plain CFG rules with a set of terminals) is the same as we've been using
  - The good thing about them is that you get exactly the semantic rules you need
  - The bad thing is that you need to develop a new grammar for each new domain
- Typically used in conversational agents in constrained domains
  - Limited vocabulary
  - Limited grammatical complexity
  - Syntactic parsing can often produce all that's needed for semantic interpretation even in the face of "ungrammatical" input – write fragment rules

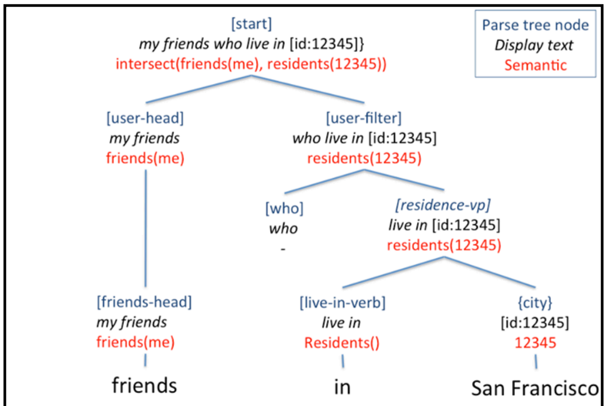
Semantic Grammars Summary

- Advantages:
  - Efficient recognition of limited domain input
  - Absence of overall grammar allows pattern-matching possibilities for idioms, etc.
  - No separate interpretation phase
  - Strength of top-down constraints allows powerful ellipsis mechanisms
    What is the length of the Kennedy? The Kittyhawk?
- Disadvantages:
  - Different grammar required for each new domain
  - Lack of overall syntax can lead to "spotty" grammar coverage
    - E.g. fronting possessive in "<attribute> of <ship>" to <ship> 's <attribute> doesn't imply fronting in "<rank> of <officer>"
  - Difficult to develop grammars past a certain size
  - Suffers from fragility

Facebook Graph Search

- Uses a weighted context free grammar (WCFG) to represent the Graph Search query language:
- [start] => [users] $1
- [users] => my friend(s)   friends(me)
- [users] => friends of [users]   friends($1)
- [users] => {user} $1
- [users] => {user} {user-filter}   intersect($1, $2)
- [start] => [photos] $1
- [photos] => photos of [users]   photos($1)
- A terminal symbol can be an entity, e.g., {user}, {city}, {employer}, {group}; it can also be a word/phrase, e.g., *friends*, *live in*, *work at*, *members*, etc. A parse tree starts from [start] and expanding via rules to terminal symbols.

https://www.facebook.com/notes/facebook-engineering/under-the-hood-the-natural-language-interface-of-graph-search/101514327330489
http://spectrum.ieee.org/telecom/internet/the-making-of-facebooks-graph-sear



The parse tree, semantic and entity ID used in the above example are for illustration only; they do not represent real information used in Graph Search Beta