# 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:

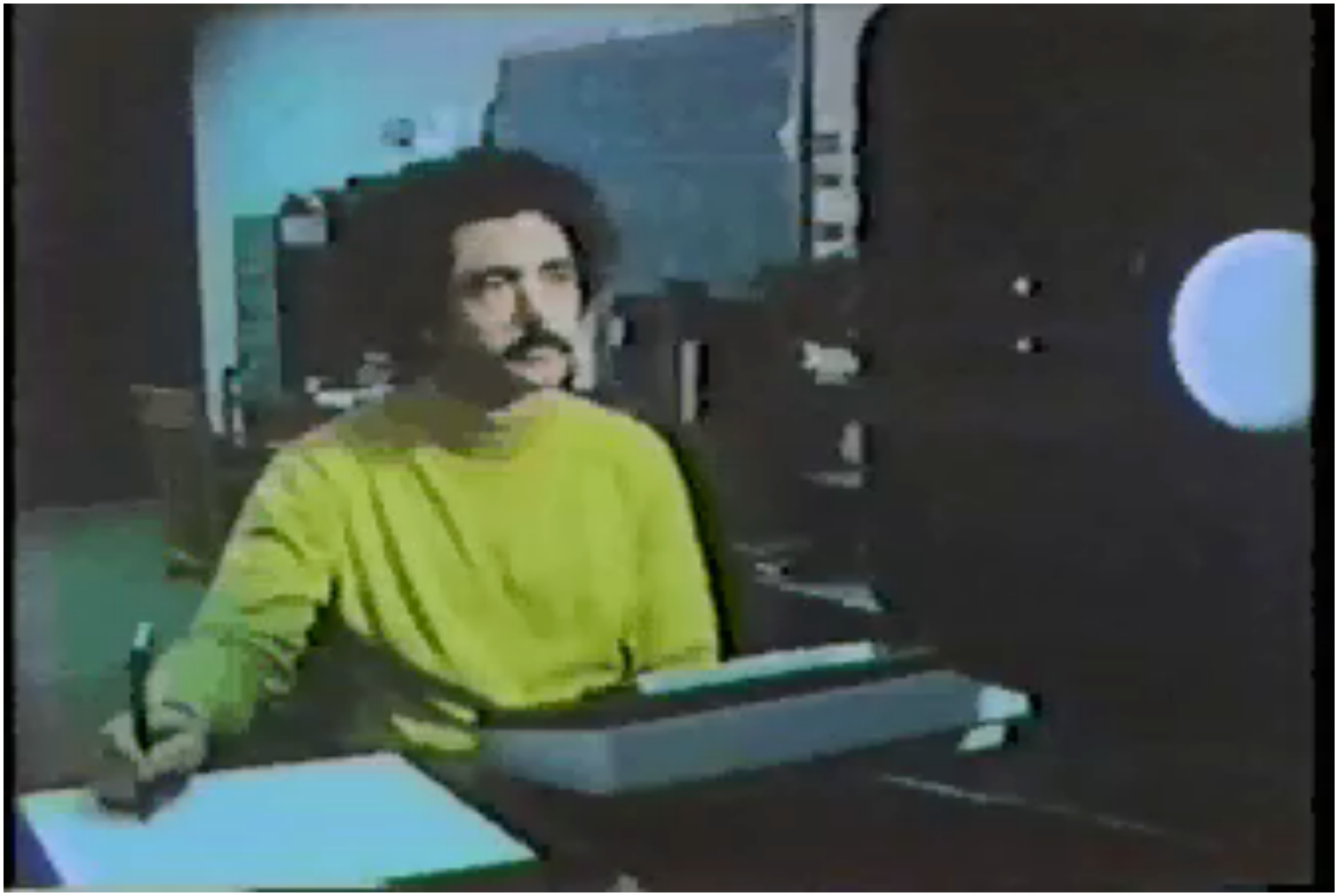
- Not all tasks can ignore language structure/meaning
- Unsuitable if new text must be generated
- Unsuitable if machine must act rather than relying on user to interpret material written by the author of the document

You get what you pay for:

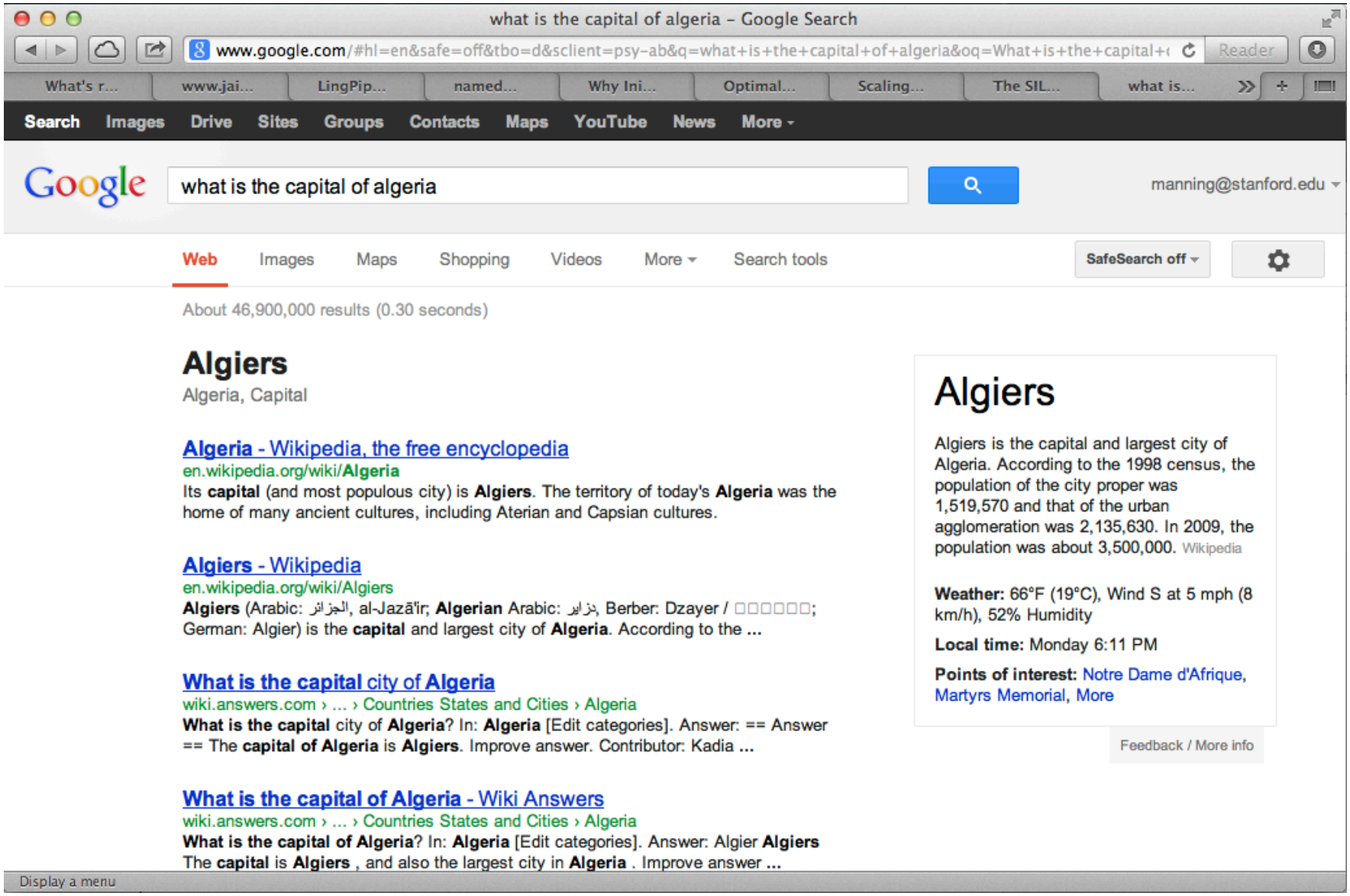
- Cheap, fast, low-level techniques are appropriate when speed and volume are more important than accuracy
- Computationally expensive, higher-level techniques are appropriate when high-quality results are required

# SHRDLU

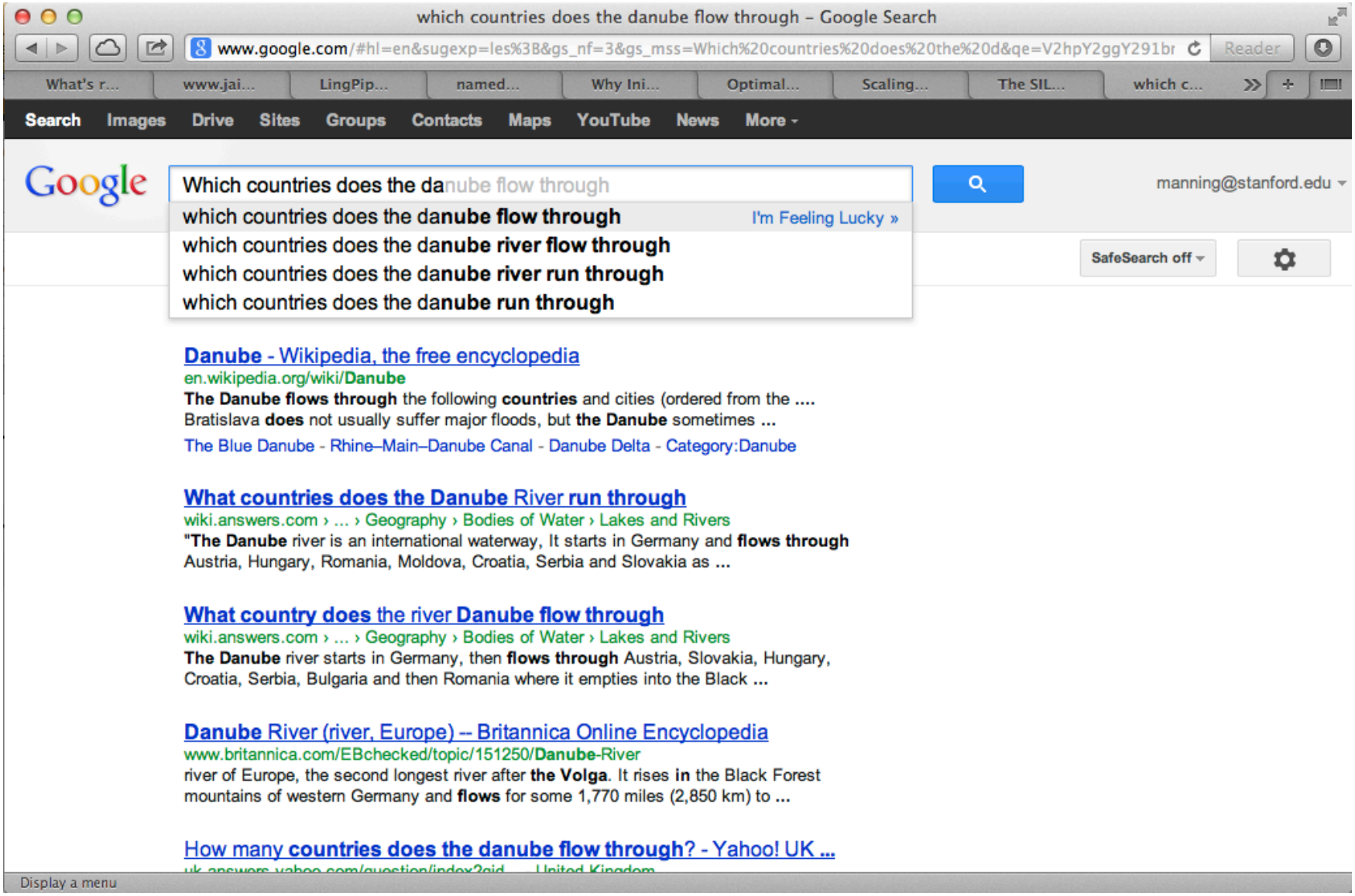
http://hci.stanford.edu/winograd/shrdlu/



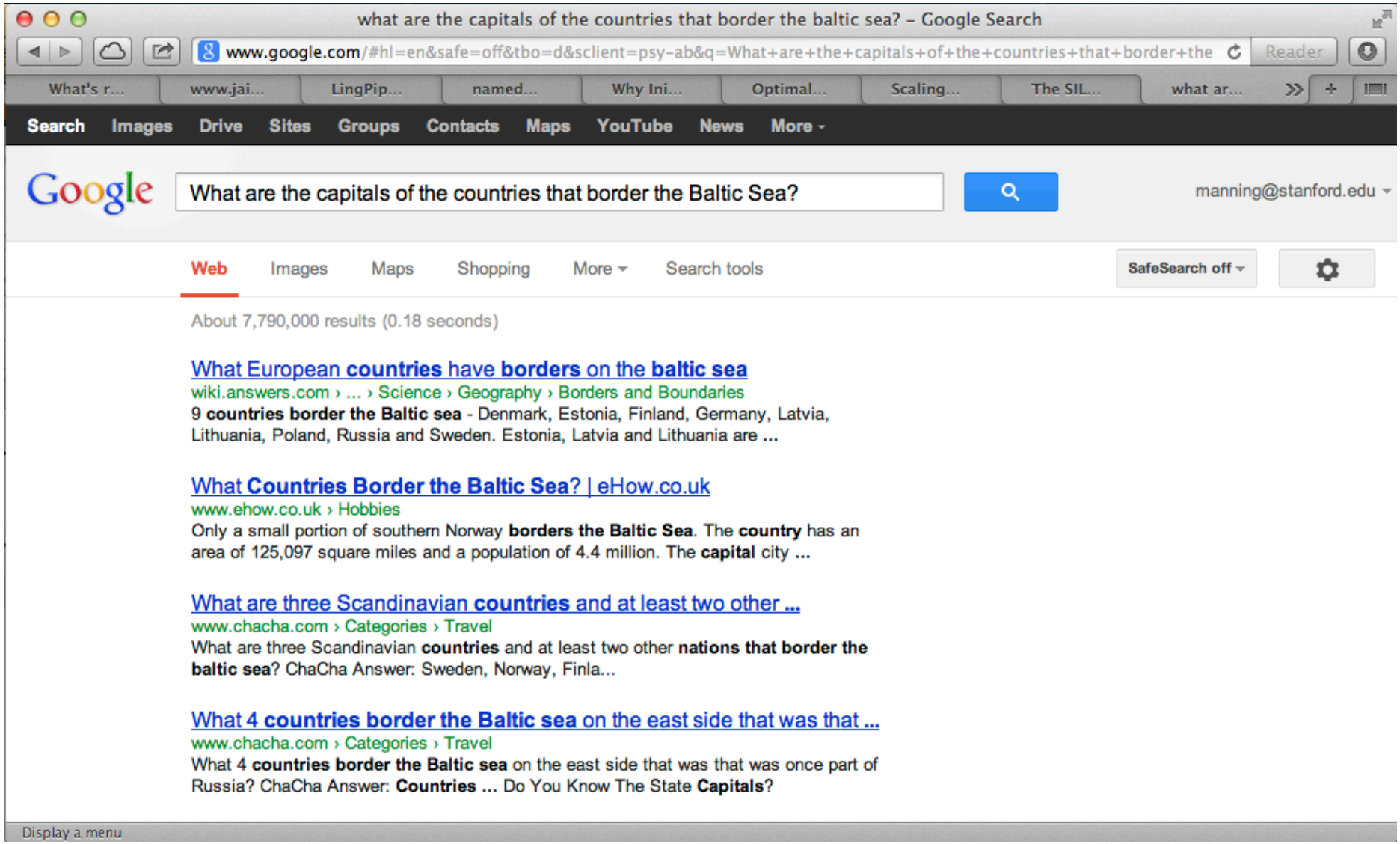
# Google: What is the capital of Algeria?



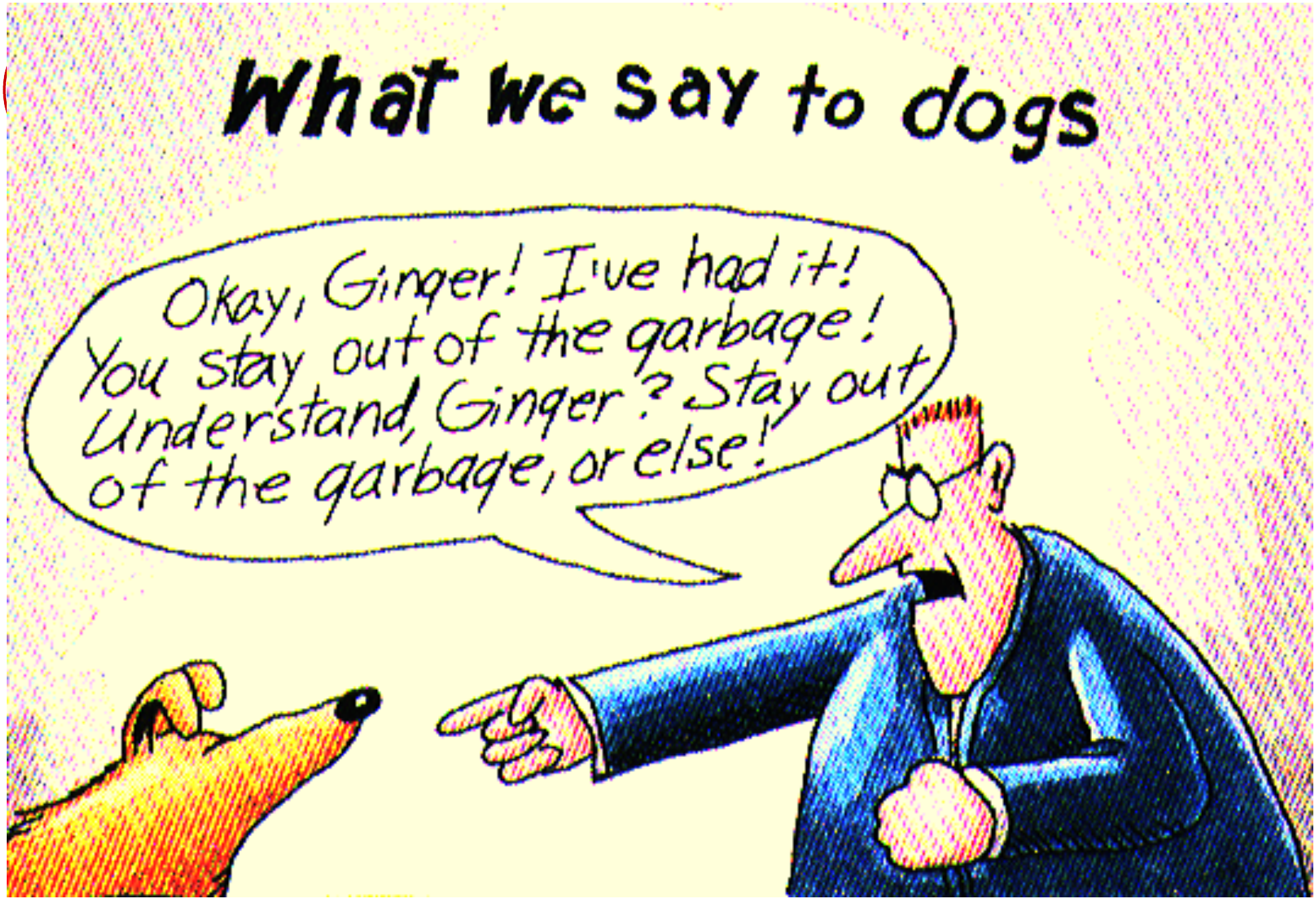
# Google: Which countries does the Danube flow through?



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



# What we say to dogs



what they hear
blah blah GINGER blah
blah blah blah blah
blah blah GINGER blah
blah blah blah blah...

# 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).
```

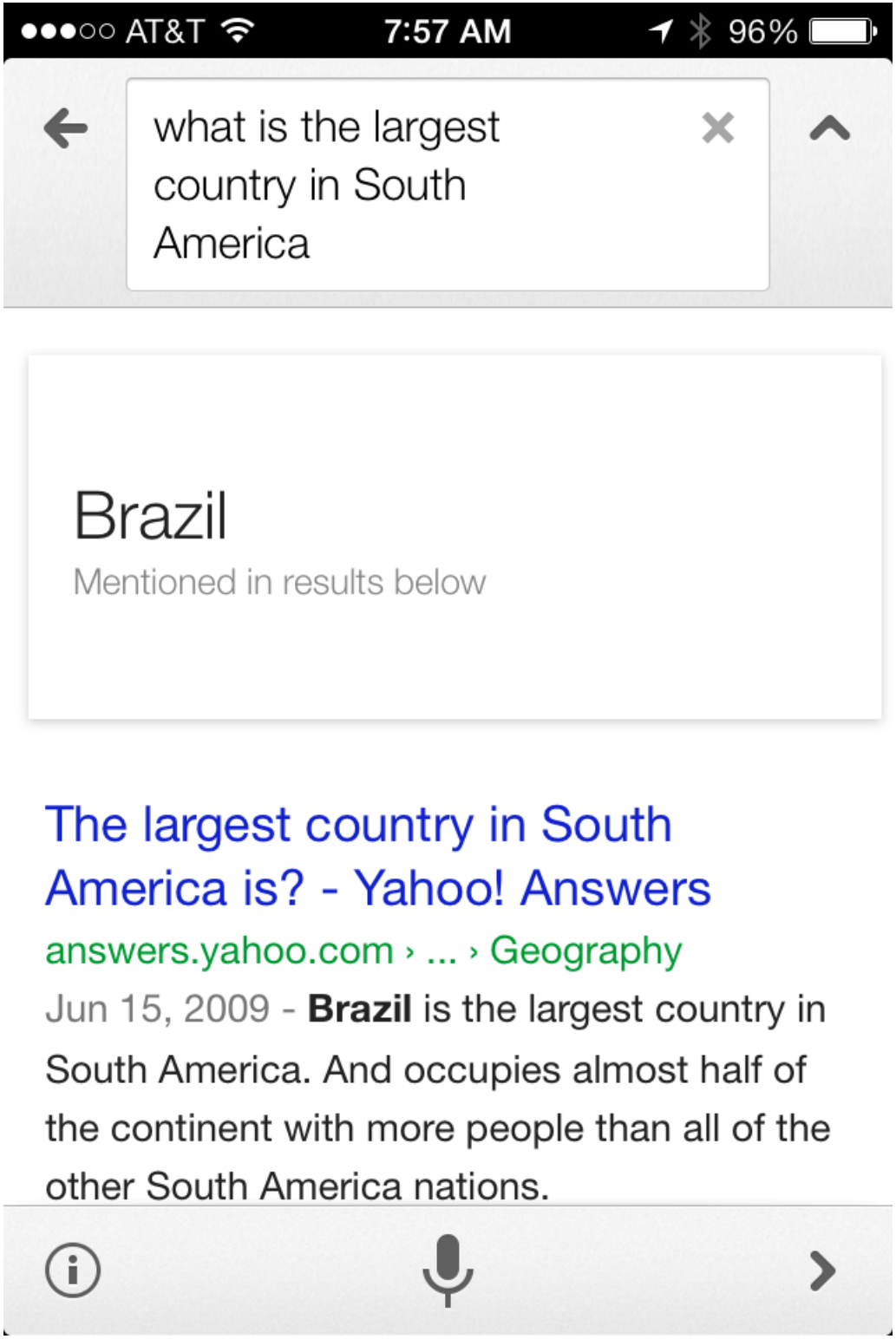
# Fast-forward to 2015

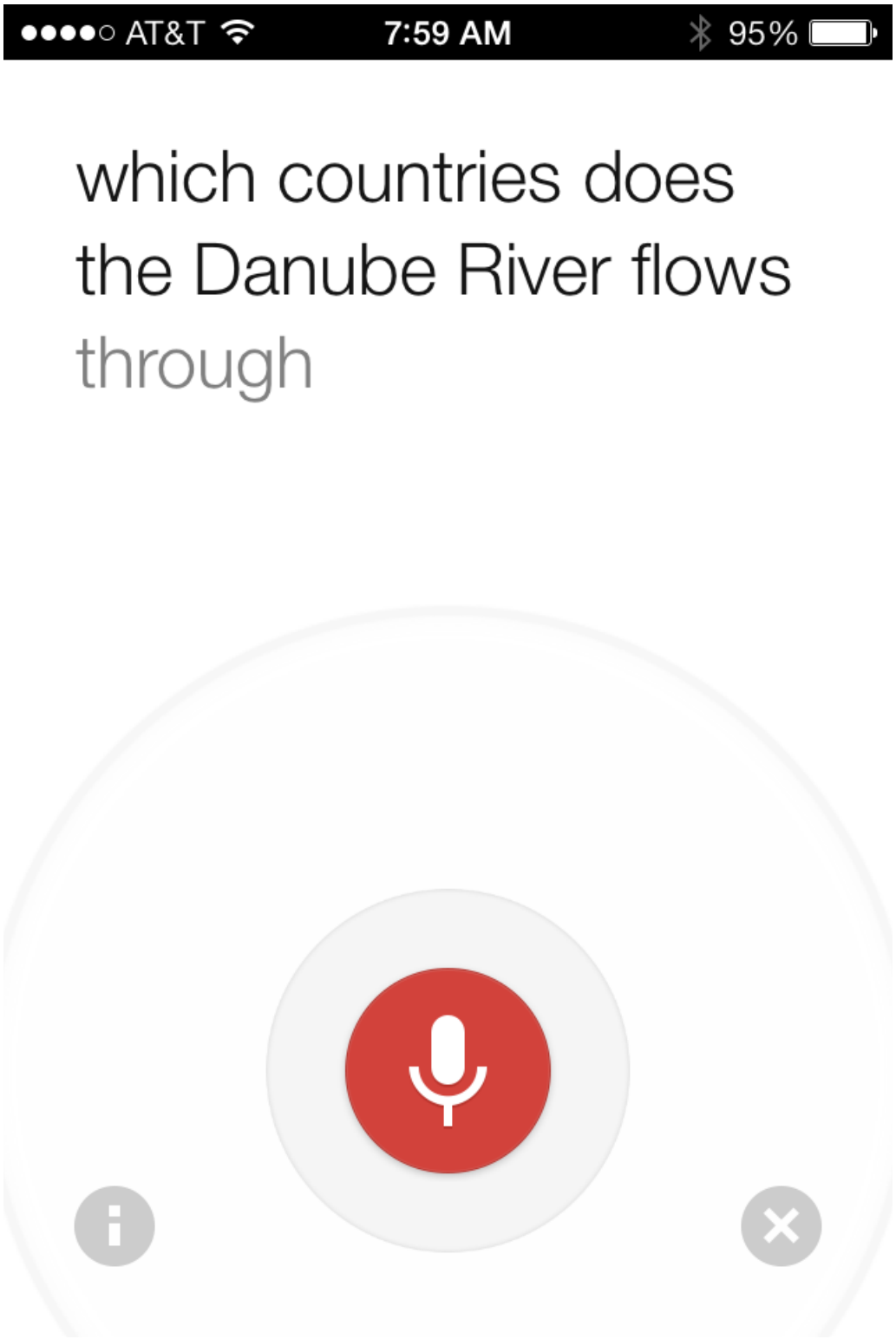
- Siri
- Google Now
- Cortana
- Amazon Echo / Alexa
- Nuance Nina
- Facebook M

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

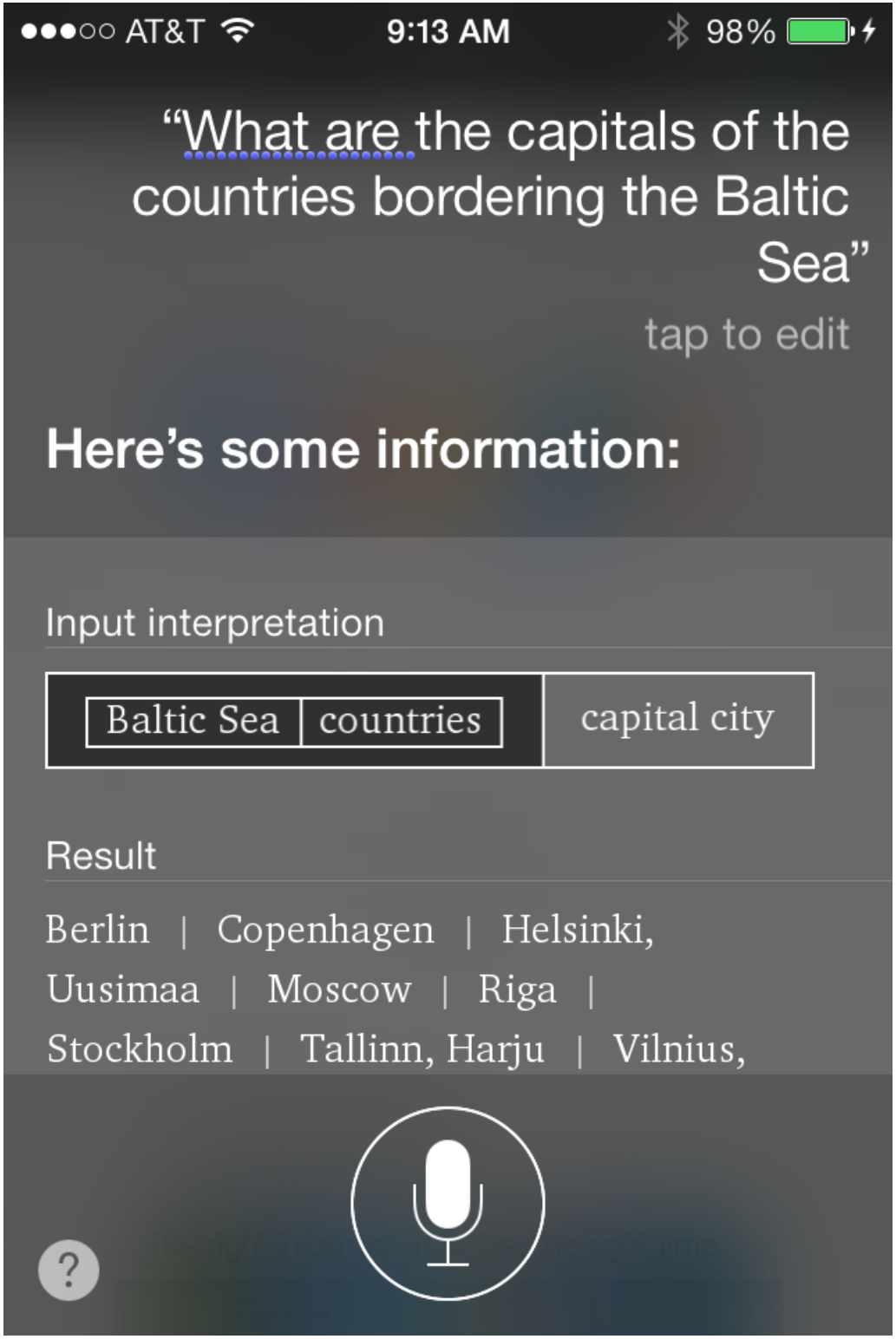
www.ask.com › ... › Environment

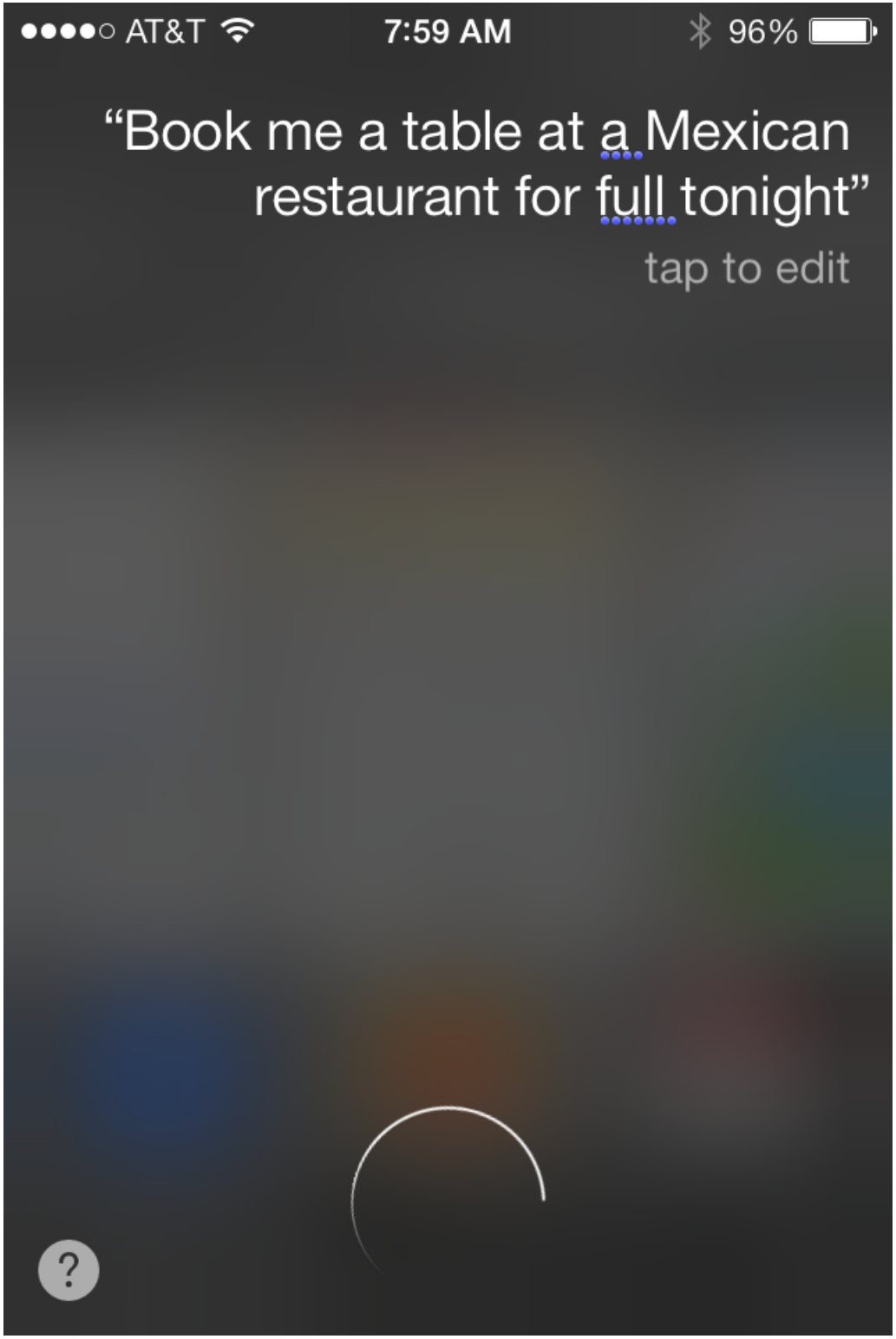
The **Countries** which the **River Danube flow through** are;Germany,Austria, Slovakia,hungary,Croatia,Serbia,Bulgaria **...**

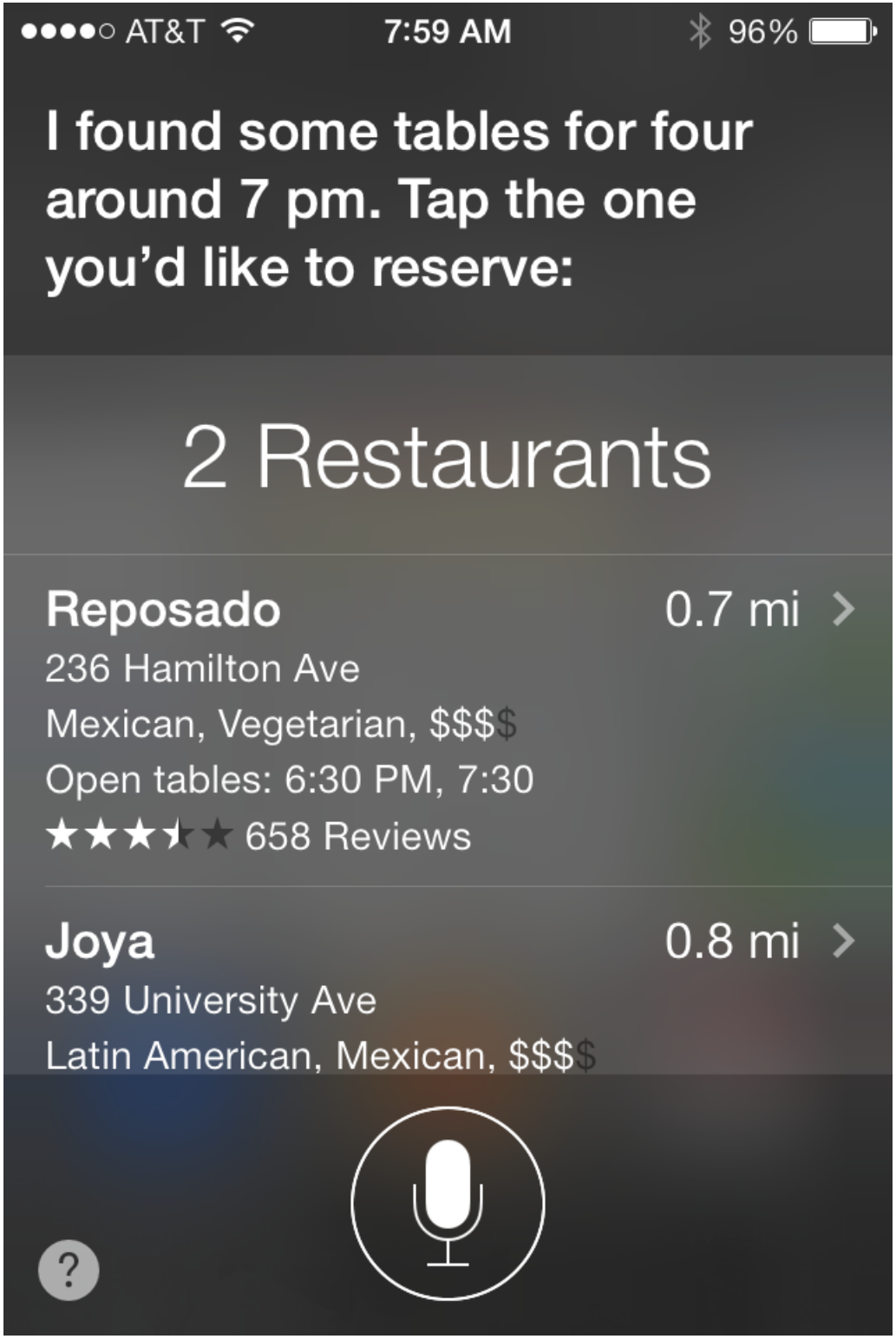
**What Countries Does the Danube River Run through** - Ask.com

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?*"

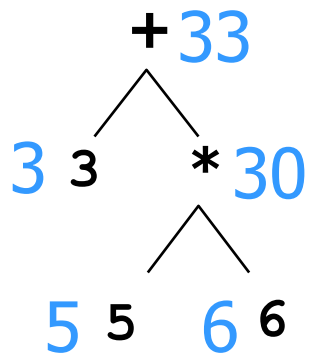
Finally, we're starting to understand some complex combinations:

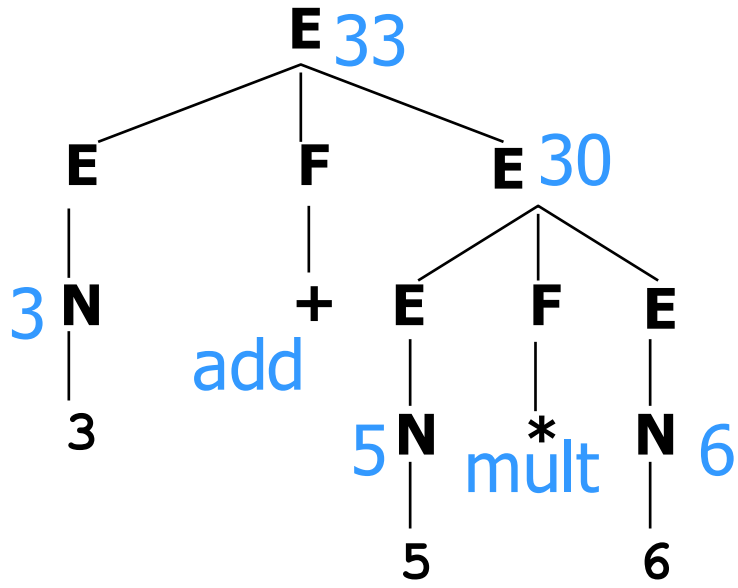
"*What are some of Seth Gabel's father-in-law's movies?*"

"*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)

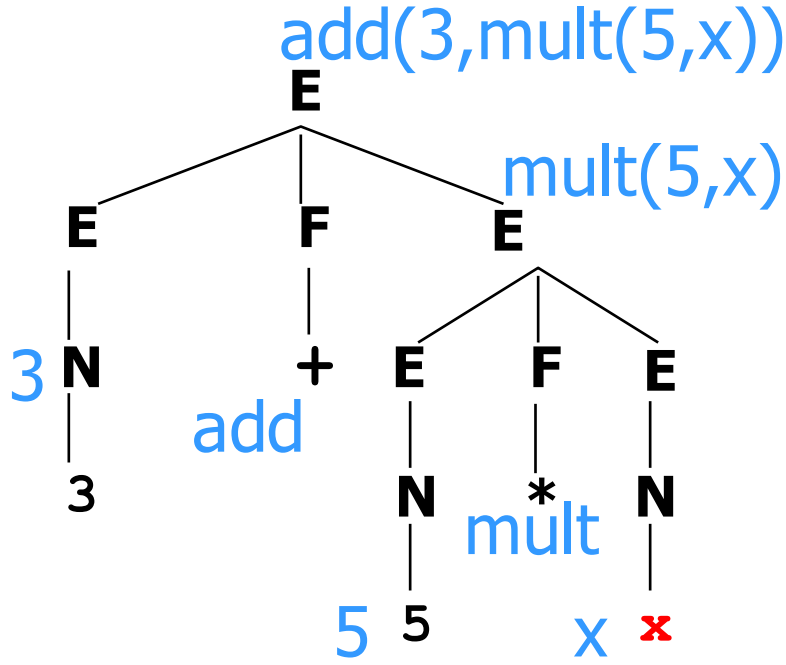


# More complex meanings

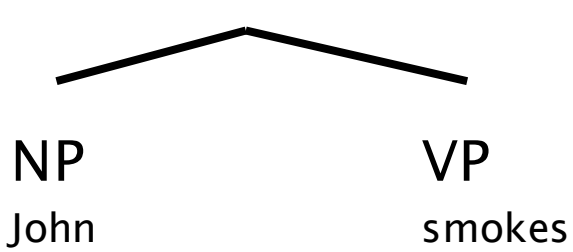
- How about `3+5*x`?
- Don't know `x` at compile time
- "Meaning" at a node is a piece of code, not a number

- 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 predicate: 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]
Proper_noun --> [Mary]
determiner --> [the]
determiner--> [a]

verb --> [ate]
verb --> [kissed]
noun --> [cake]
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].
det(s) --> [the].
det(p) --> [the].
```

```
noun(s) --> [lion].
noun(p) --> [lions].
verb(s) --> [eats].
verb(p) --> [eat].
```

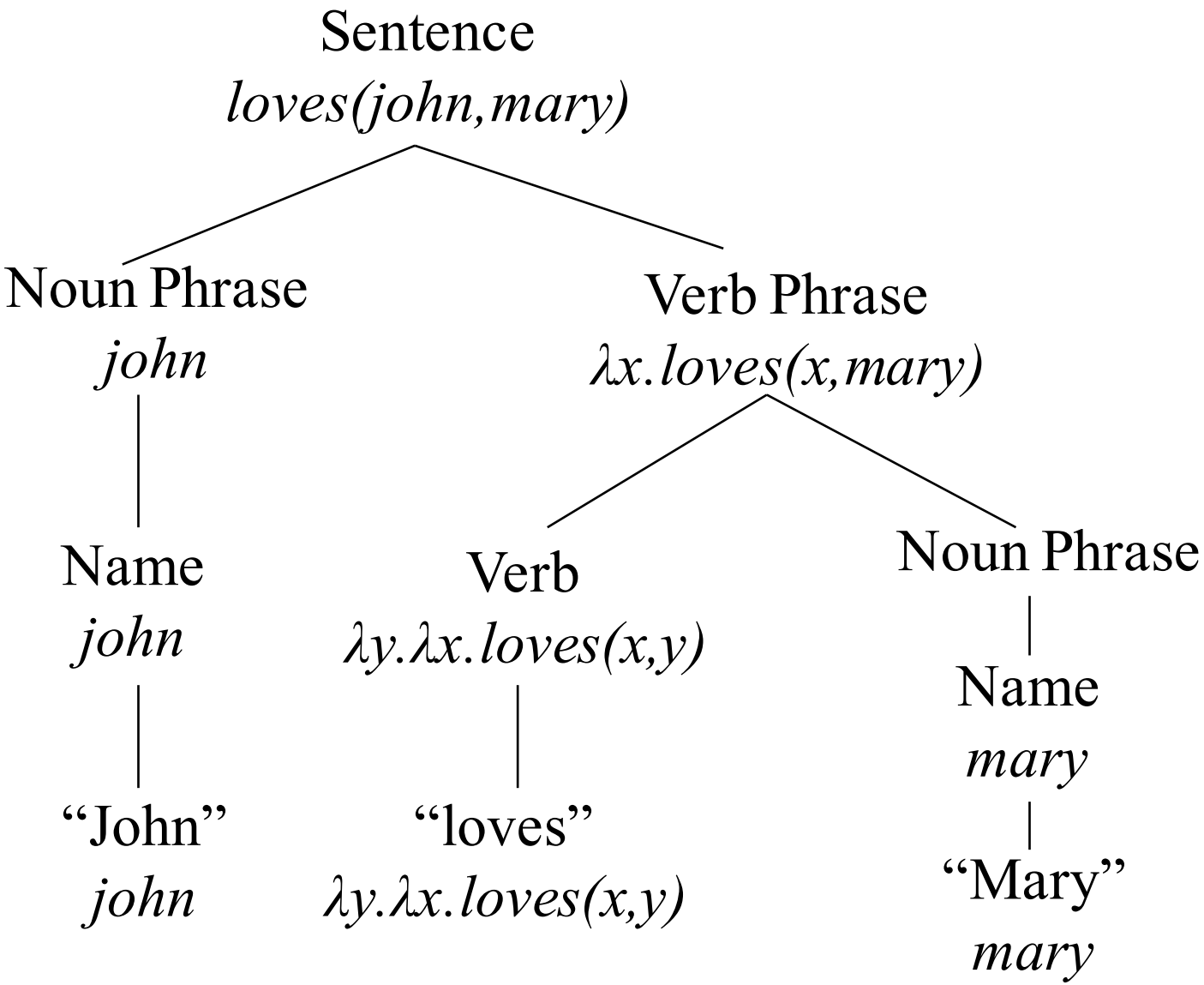
# A simple DCG grammar with semantics

```
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 a woman gives birth every 15 min. 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

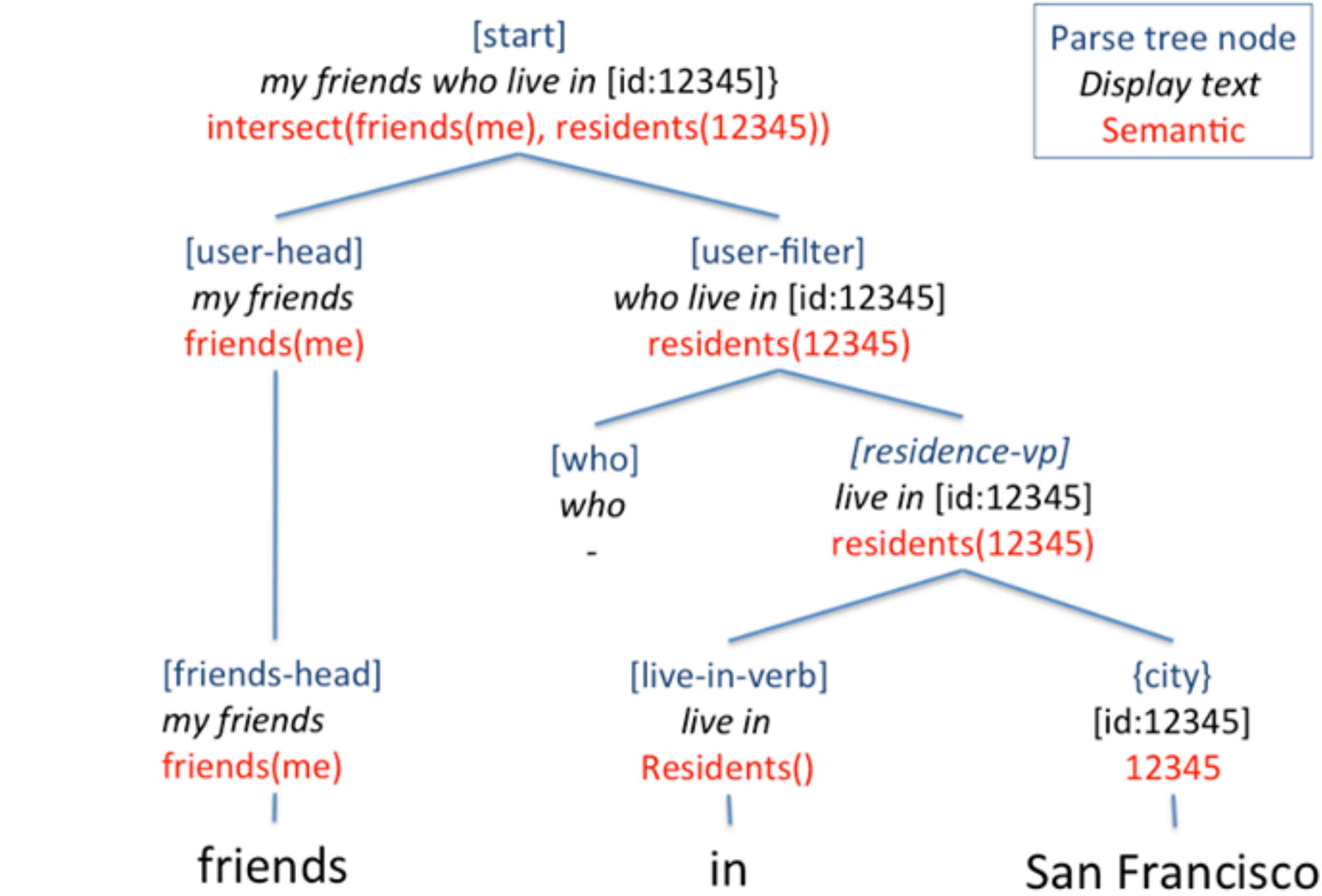
- Advantages:
  - Efficient recognition of limited domain input
  - Absence of overall grammar allows pattern-matching possibilities for idioms, etc.
  - No separate interpretation phase
  - Strength of top-down constraints allows powerful ellipsis mechanisms

    *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/10151432733048920
http://spectrum.ieee.org/telecom/internet/the-making-of-facebooks-graph-search




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