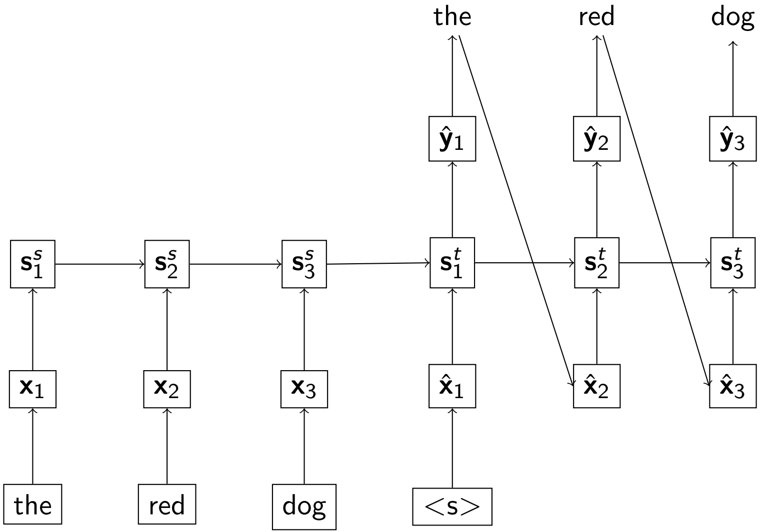
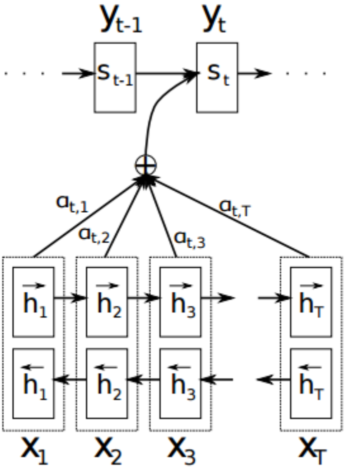
Question Answering/Semantic Parsing

CS 287

(Slides from Yoav Artzi, Cornell NY)

Sequence-to-Sequence




y_{t-1}
y_t
s_{t-1}
s_t
$\alpha_{t,1}$
$\alpha_{t,2}$
$\alpha_{t,3}$
$\alpha_{t,T}$
$\overrightarrow{h}_1$
$\overrightarrow{h}_2$
$\overrightarrow{h}_3$
$\overrightarrow{h}_T$
$\overleftarrow{h}_1$
$\overleftarrow{h}_2$
$\overleftarrow{h}_3$
$\overleftarrow{h}_T$
x_1
x_2
x_3
x_T

Question

It has become a popular strategy to handle sequential prediction problems using a seq2seq setup such as attention-based translation. How might you handle the following problems:

1. Segmentation (HW4)
2. Rare Word Replacement (HW3)
3. Part-of-Speech Tagging (HW2-HW5)

Semantics

Branch of linguistic focused on meaning

- Lexical Semantics
  - Meaning of individual words
  - e.g. BoW models, word2vec
- Compositional Semantics
  - Meaning of utterances
  - Concerned with the relations of meaning
  - Often expressed with logical relations

Today's Lecture

Survey of Question Answering

- Semantic Parsing: Linguistic model of questions and answers
- Knowledge Bases and Datasets
- IR-style approaches: Watson and Jeopardy!

Contents

Lambda Calculus

- Formal system to express computation
- Allows high-order functions

$$\lambda a.move(a) \wedge dir(a, LEFT) \wedge to(a, \iota y.chair(y)) \wedge$$
$$pass(a, \mathcal{A}y.sofa(y) \wedge intersect(\mathcal{A}z.intersection(z), y))$$

[Church 1932]

Lambda Calculus
Base Cases

- Logical constant
- Variable
- Literal
- Lambda term

Lambda Calculus
Logical Constants

- Represent objects in the world

$$NYC, CA, RAINIER, LEFT, \ldots$$
$$located\_in, depart\_date, \ldots$$

Lambda Calculus
Variables

- Abstract over objects in the world
- Exact value not pre-determined

$$x, y, z, \ldots$$

Lambda Calculus
Literals

- Represent function application

$$city(AUSTIN)$$

$$located\_in(AUSTIN, TEXAS)$$

Lambda Calculus

Literals

- Represent function application

$$city(AUSTIN)$$

$$\underbrace{located\_in}_{\text{Predicate}}(\underbrace{AUSTIN, TEXAS}_{\text{Arguments}})$$

Logical expression

List of logical expressions

Lambda Calculus
Lambda Terms

- Bind/scope a variable
- Repeat to bind multiple variables

$$\lambda x.city(x)$$

$$\lambda x.\lambda y.located\_in(x, y)$$

Lambda Calculus

Lambda Terms

- Bind/scope a variable
- Repeat to bind multiple variables

$$\lambda x.city(x)$$

$$\lambda x.\underbrace{\lambda}_{\text{Lambda operator}}\underbrace{y}_{\text{Variable}}.\underbrace{located\_in(x, y)}_{\text{Body}}$$

Lambda Calculus
Quantifiers?

- Higher order constants
- No need for any special mechanics
- Can represent all of first order logic

$$\forall(\lambda x.big(x) \wedge apple(x))$$
$$\neg(\exists(\lambda x.lovely(x))$$
$$\iota(\lambda x.beautiful(x) \wedge grammar(x))$$

Lambda Calculus
Syntactic Sugar

$$\wedge\,(A, \wedge(B, C)) \Leftrightarrow A \wedge B \wedge C$$

$$\vee\,(A, \vee(B, C)) \Leftrightarrow A \vee B \vee C$$

$$\neg(A) \Leftrightarrow \neg A$$

$$\mathcal{Q}(\lambda x.f(x)) \Leftrightarrow \mathcal{Q}x.f(x)$$

$$\text{for } \mathcal{Q} \in \{\iota, \mathcal{A}, \exists, \forall\}$$

$$\lambda x.flight(x) \wedge to(x, move)$$
$$\lambda x.flight(x) \wedge to(x, NYC)$$
$$\lambda x.NYC(x) \wedge x(to, move)$$

✗ $\lambda x.flight(x) \wedge to(x, move)$

✓ $\lambda x.flight(x) \wedge to(x, NYC)$

✗ $\lambda x.NYC(x) \wedge x(to, move)$

Simply Typed Lambda Calculus

- Like lambda calculus
- But, typed

✗ $\lambda x.flight(x) \wedge to(x, move)$

✓ $\lambda x.flight(x) \wedge to(x, NYC)$

✗ $\lambda x.NYC(x) \wedge x(to, move)$

[Church 1940]

Lambda Calculus

Typing

t Truth-value

e Entity

- Simple types
- Complex types

$$< e, t >$$

$$<< e, t >, e >$$

Lambda Calculus

Typing

t Truth-value

e Entity

- Simple types
- Complex types

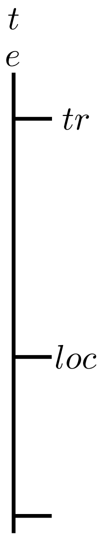
Type constructor

$$< e, t >$$

$$<\underbrace{< e, t >}_{\text{Domain}}, \underbrace{e}_{\text{Range}} >$$

Lambda Calculus

Typing



- Simple types
- Complex types

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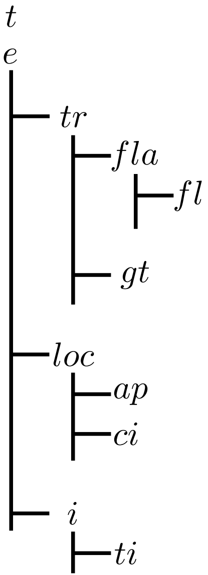
- Hierarchical typing system

Lambda Calculus

Typing



- Simple types
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Type constructor

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- Hierarchical typing system

Simply Typed Lambda Calculus

$$\lambda a.move(a) \wedge dir(a, LEFT) \wedge to(a, \iota y.chair(y)) \wedge$$
$$pass(a, \mathcal{A}y.sofa(y) \wedge intersect(\mathcal{A}z.intersection(z), y))$$

Type information usually omitted

Capturing Meaning with Lambda Calculus

State

Abbr.	Capital	Pop.
AL	Montgomery	3.9
AK	Juneau	0.4
AZ	Phoenix	2.7

Border

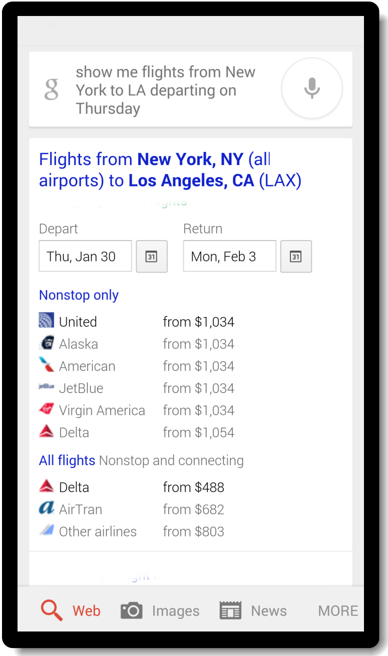
State1	State2
WA	OR
WA	ID
CA	OR
CA	NV
CA	AZ

Mountains

Name	State
Bianca	CO
Antero	CO
Rainier	WA
Shasta	CA
Wrangel	AK
Si	
Bo	

Show me mountains in states bordering Texas

[Zettlemoyer and Collins 2005]


show me flights from New York to LA departing on Thursday
Flights from New York, NY (all airports) to Los Angeles, CA (LAX)
Depart
Thu, Jan 30
Return
Mon, Feb 3
Nonstop only
United from $1,034
Alaska from $1,034
American from $1,034
JetBlue from $1,034
Virgin America from $1,034
Delta from $1,054
All flights Nonstop and connecting
Delta from $488
AirTran from $682
Other airlines from $803
Web
Images
News
MORE

Parsing as Structure Prediction

$$
\begin{array}{cccc}
\text{show} \quad \text{me} & \text{flights} & \text{to} & \text{Boston} \\
\hline
S/N & N & PP/NP & NP \\
\lambda f.f & \lambda x.flight(x) & \lambda y.\lambda x.to(x,y) & BOSTON
\end{array}
$$

$$\xrightarrow{\quad\quad\quad\quad\quad\quad}>$$

$$PP$$
$$\lambda x.to(x, BOSTON)$$

$$\overline{\quad\quad\quad\quad\quad\quad}$$

$$N\backslash N$$
$$\lambda f.\lambda x.f(x) \wedge to(x, BOSTON)$$

$$\xrightarrow{\quad\quad\quad\quad\quad\quad}<$$

$$N$$
$$\lambda x.flight(x) \wedge to(x, BOSTON)$$

$$\xrightarrow{\quad\quad\quad\quad\quad\quad}>$$

$$S$$
$$\lambda x.flight(x) \wedge to(x, BOSTON)$$

Contents

Dataset: Geoquery

- Maps natural language questions to lambda calculus.
- Assume a database with numerical values as well (`population(TEXAS)`)
- Queries contain rich nesting

```
size(stateid(X), S) :-
area(stateid(X), S).
size(cityid(X,St), S) :-
population(cityid(X,St), S).
size(riverid(X), S) :-
len(riverid(X),S).
size(placeid(X), S) :-
elevation(placeid(X),S).
size(X,X) :-
number(X).

next_to(stateid(X),stateid(Y)) :-
border(X,_,Ys),
member(Y,Ys).
```

Quiz: Geoquery

- What states border Texas?
- What is the largest state?
- What states border the state that borders the most state?

(Syntactic Sugar: $\arg\max(f, g)$ returns max of element of g that satisfies predicate f.)

Geoquery (Zelle and Mooney, 1996)

a) What states border Texas
$\lambda x.state(x) \wedge borders(x, texas)$

b) What is the largest state
$\arg\max(\lambda x.state(x), \lambda x.size(x))$

c) What states border the state that borders the most states
$$\lambda x.state(x) \wedge borders(x, \arg\max(\lambda y.state(y), \lambda y.count(\lambda z.state(z) \wedge borders(y, z))))$$

Figure 1: Examples of sentences with their logical forms.

WebQuestions (Berant, 2013)

Questions:

- what high school did president bill clinton attend?
- what form of government does russia have today?
- what movies does taylor lautner play in?

Answers:

- Hot Springs High School
  `http://www.freebase.com/view/en/bill_clinton`
- Constitutional republic
  `http://www.freebase.com/view/en/russia`
- Eclipse, Valentine's Day, The Twilight Saga: Breaking Dawn - Part 1, New Moon
  `http://www.freebase.com/view/en/taylor_lautner`

Here's an example:

We know that William Shakespeare wrote the play Hamlet. We describe this in Freebase as such:

William Shakespeare

is a	type	Author
has a	property	Works Written
with a	value	Hamlet

Freebase Find... Browse Query Help Sign In or Sign Up English

Important! Freebase is read-only and will be shut-down. More.

Topic

Abraham Lincoln en

mid: /m/0gzh **notable type:** /government/us_president **notable for:** /government/us_president **on the web:** wikipedia.org

Created by book_bot on 5/7/2009

Abraham Lincoln was the 16th president of the United States, serving from March 1861 until his assassination in April 1865. Lincoln led the United States through its Civil War—its bloodiest war and its greatest moral, constitutional and political crisis. In doing so, he preserved the Union, abolished slavery, strengthened the federal government, and modernized the economy. Reared in a poor family on the western frontier, Lincoln was a self-educated lawyer in Illinois, a Whig Party leader, state legislator during the 1830s. Lincoln was elected to Congress in 1846, where he promoted rapid modernization of the economy through banks, tariffs, and railroads. He had originally agreed not to run for a second term and his opposition to the Mexican–American War was unpopular among the voters. He returned to Springfield and concentrated on his successful law practice throughout central Illinois. He returned to politics in 1854, and was a leader in building up the new Republican Party, which was had a statewide majority. After a series of highly publicized debates in 1858, during which Lincoln spoke out against the expansion of slavery, he lost the U.S. [-]

Properties | I18n | Keys | Links

View and edit specific domains, types, or properties...

Filter options: Show all domains and properties

Common /common

Freebase Commons

Topic /common/topic

- **Also known as** /common/topic/alias

Also known as

Honest Abe
Abe Lincoln
The Buffoon
Caesar
Father Abraham
The Flatboat Man
The Grand Wrestler
The Great Emancipator
The Illinois Baboon
The Jester

58 values total »

Description /common/topic/description

Abraham Lincoln was the 16th president of the United States, serving from March 1861 until his assassination in April 1865. Lincoln led the United States through its Civil War—its bloodiest war and its greatest moral, constitutional and political crisis. In doing so, he preserved the Union, abolished slavery, strengthened the federal government, and modernized the economy. Reared in a poor family on the western frontier, Lincoln was a self-educated lawyer in Illinois, a Whig Party leader, state legislator during the 1830s. Lincoln was elected to Congress in 1846, where he promoted rapid modernization of the economy through banks, tariffs, and railroads. He

Types:

Common
Topic

Film
Film story contributor
Film subject

Government
US President
Politician
Political Appointer
U.S. Congressperson

Medicine
Public figure with medical condition

Military
Military Person
Military Commander

Books
Literature Subject

Aあ English · Not logged in · Talk · Contributions · Create account · Log in

Item · Discussion · Read · View history · Search

Abraham Lincoln (Q91)

16th President of the United States

Abe Lincoln | Lincoln | Honest Abe

In more languages Configure

Language	Label	Description	Also known as
English	Abraham Lincoln	16th President of the United States	Abe Lincoln Lincoln Honest Abe
German	Abraham Lincoln	US-amerikanischer Präsident	
Spanish	Abraham Lincoln	decimosexto presidente de los Estados Unidos	
Traditional Chinese	亚伯拉罕·林肯	第16任美國總統	林肯

More languages

Statements

family name	Lincoln 0 references
given name	Abraham 0 references
manner of death	homicide 0 references

Main page
Community portal
Project chat
Create a new item
Item by title
Recent changes
Random item
Query Service
Nearby
Help
Donate

Print/export
Create a book
Download as PDF
Printable version

Tools
What links here
Related changes
Special pages
Permanent link
Page information
Concept URI
Cite this page

WebQuestions

To collect this dataset, we used the Google Suggest API to obtain questions that begin with a whword and contain exactly one entity. We started with the question Where was Barack Obama born? and performed a breadth-first search over questions (nodes), using the Google Suggest API supplying the edges of the graph. Specifically, we queried the question excluding the entity, the phrase before the entity, or the phrase after it; each query generates 5 candidate questions, which are added to the queue. We iterated until 1M questions were visited; a random 100K were submitted to Amazon Mechanical Turk.

WebQuestions

The AMT task requested that workers answer the question using only the Freebase page of the questions entity, or otherwise mark it as unanswerable by Freebase. The answer was restricted to be one of the possible entities, values, or list of entities on the page. As this list was long, we allowed the user to filter the list by typing. We paid the workers $0.03 per question. Out of 100K questions, 6,642 were annotated identically by at least two AMT workers.

Dataset	# examples	# word types
GeoQuery	880	279
ATIS	5,418	936
FREE917	917	2,036
WEBQUESTIONS	5,810	4,525

Table 3: Statistics on various semantic parsing datasets. Our new dataset, WEBQUESTIONS, is much larger than FREE917 and much more lexically diverse than ATIS.

Contents

Language to Meaning

Semantic Parsing

Recover **complete** meaning representation

More informative

Example Task

Database Query

What states border Texas?

Oklahoma
New Mexico
Arkansas
Louisiana

Language to Meaning

Semantic Parsing

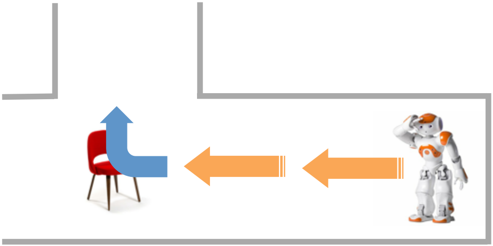
Recover **complete** meaning representation

More informative

Example Task

Instructing a Robot

at the chair,
turn right



Language to Meaning

at the chair, move forward three steps past the sofa

$$\lambda a.pre(a, \iota x.chair(x)) \land move(a) \land len(a, 3) \land$$
$$dir(a, forward) \land past(a, \iota y.sofa(y))$$

Language to Meaning

at the chair, move forward three steps past the sofa

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Learn

$$f : \text{sentence} \rightarrow \text{logical form}$$

Language to Meaning

at the chair, move forward three steps past the sofa

Learn

$$f : \text{sentence} \to \text{logical form}$$

Supervised Data

$$
\begin{array}{ccccl}
\text{show} \quad \text{me} & \text{flights} & \text{to} & \text{Boston} & \\
\cline{1-1} \cline{2-2} \cline{3-3} \cline{4-4}
S/N & N & PP/NP & NP & \\
\lambda f.f & \lambda x.flight(x) & \lambda y.\lambda x.to(x,y) & BOSTON & \\
\cline{3-4}
 & & \multicolumn{2}{c}{PP} & > \\
 & & \multicolumn{2}{c}{\lambda x.to(x,BOSTON)} & \\
\cline{3-4}
 & & \multicolumn{2}{c}{N\backslash N} & \\
 & & \multicolumn{2}{c}{\lambda f.\lambda x.f(x) \wedge to(x,BOSTON)} & \\
\cline{2-4}
 & \multicolumn{3}{c}{N} & < \\
 & \multicolumn{3}{c}{\lambda x.flight(x) \wedge to(x,BOSTON)} & \\
\cline{1-4}
\multicolumn{4}{c}{S} & > \\
\multicolumn{4}{c}{\lambda x.flight(x) \wedge to(x,BOSTON)} & \\
\end{array}
$$

Supervised Data

show me	flights	to	Boston
S/N	N	PP/NP	NP
$\lambda f.f$	$\lambda x.flight(x)$	$\lambda y.\lambda x.to(x,y)$	$BOSTON$

$$\frac{PP/NP \quad NP}{PP} >$$

$$\lambda x.to(x, BOSTON)$$

$$N\backslash N$$

$$\lambda f.\lambda x.f(x) \wedge to(x, BOSTON)$$

$$N \quad <$$

$$\lambda x.flight(x) \wedge to(x, BOSTON)$$

$$S \quad >$$

$$\lambda x.flight(x) \wedge to(x, BOSTON)$$

Latent

Supervised Data

Supervised learning is done from pairs of sentences and logical forms

Show me flights to Boston
$\lambda x.flight(x) \wedge to(x, BOSTON)$

I need a flight from baltimore to seattle
$\lambda x.flight(x) \wedge from(x, BALTIMORE) \wedge to(x, SEATTLE)$

what ground transportation is available in san francisco
$\lambda x.ground\_transport(x) \wedge to\_city(x, SF)$

[Zettlemoyer and Collins 2005; 2007]

Weak Supervision

- Logical form is latent
- "Labeling" requires less expertise
- Labels don't uniquely determine correct logical forms
- Learning requires executing logical forms within a system and evaluating the result

Weak Supervision
Learning from Query Answers

What is the largest state that borders Texas?

$$New\ Mexico$$

[Clarke et al. 2010; Liang et al. 2011]

Weak Supervision
Learning from Query Answers

What is the largest state that borders Texas?

$$New\ Mexico$$

$$argmax(\lambda x.state(x)$$
$$\wedge\, border(x, TX), \lambda y.size(y))$$

$$argmax(\lambda x.river(x)$$
$$\wedge\, in(x, TX), \lambda y.size(y))$$

[Clarke et al. 2010; Liang et al. 2011]

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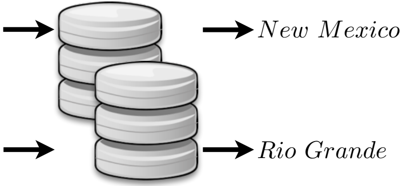

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$\rightarrow New\ Mexico$ ✓

$\rightarrow Rio\ Grande$ ✗

[Clarke et al. 2010; Liang et al. 2011]

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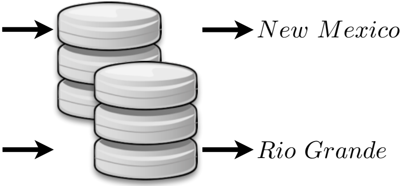

[Clarke et al. 2010; Liang et al. 2011]

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$\rightarrow New\ Mexico$ ✓

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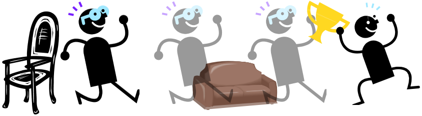
[Clarke et al. 2010; Liang et al. 2011]

Weak Supervision

Learning from Demonstrations

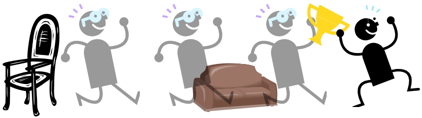
at the chair, move forward three steps past the sofa



[Chen and Mooney 2011; Kim and Mooney 2012; Artzi and Zettlemoyer 2013b]

Weak Supervision
Learning from Demonstrations

at the chair, move forward three steps past the sofa



Some examples from other domains:

- Sentences and labeled game states [Goldwasser and Roth 2011]
- Sentences and sets of physical objects [Matuszek et al. 2012]

[Chen and Mooney 2011; Kim and Mooney 2012; Artzi and Zettlemoyer 2013b]

Weak Supervision
Learning from Conversation Logs

SYSTEM how can I help you ? (OPEN_TASK)

USER i ' d like to fly to new york

SYSTEM flying to new york . (CONFIRM: $from(fl, ATL)$) leaving what city ? (ASK: $\lambda x.from(fl,x)$)

USER from boston on june seven with american airlines

SYSTEM flying to new york . (CONFIRM: $to(fl, NYC)$) what date would you like to depart boston ? (ASK: $\lambda x.date(fl,x) \wedge to(fl, BOS)$)

USER june seventh

[CONVERSATION CONTINUES]

[Artzi and Zettlemoyer 2011]

Parsing

Learning

Modeling

- Structured perceptron
- A unified learning algorithm
- Supervised learning
- Weak supervision

Structured Perceptron

- Simple additive updates
  - Only requires efficient decoding (argmax)
  - Closely related to MaxEnt and other feature rich models
  - Provably finds linear separator in finite updates, if one exists
- Challenge: learning with hidden variables

Structured Perceptron

Data: $\{(x_i, y_i) : i = 1 \ldots n\}$

For $t = 1 \ldots T$: [iterate epochs]

For $i = 1 \ldots n$: [iterate examples]

$y^* \leftarrow \arg\max_y \langle \theta, \Phi(x_i, y) \rangle$ [predict]

If $y^* \neq y_i$: [check]

$\theta \leftarrow \theta + \Phi(x_i, y_i) - \Phi(x_i, y^*)$ [update]

[Collins 2002]

One Derivation of the Perceptron

Log-linear model: $p(y|x) = \frac{e^{w \cdot f(x,y)}}{\sum_{y'} e^{w \cdot f(x,y')}}$

Step 1: Differentiate, to maximize data log-likelihood

$$update = \sum_i f(x_i, y_i) - E_{p(y|x_i)} f(x_i, y)$$

Step 2: Use online, stochastic gradient updates, for example i:

$$update_i = f(x_i, y_i) - E_{p(y|x_i)} f(x_i, y)$$

Step 3: Replace expectations with maxes (Viterbi approx.)

$$update_i = f(x_i, y_i) - f(x_i, y^*) \text{ where } y^* = \arg\max_y w \cdot f(x_i, y)$$

The Perceptron with Hidden Variables

Log-linear model: $p(y|x) = \sum_h p(y, h|x)$ $\quad p(y, h|x) = \frac{e^{w \cdot f(x,h,y)}}{\sum_{y',h'} e^{w \cdot f(x,h',y')}}$

Step 1: Differentiate marginal, to maximize data log-likelihood

$$update = \sum_i E_{p(h|y_i,x_i)}[f(x_i, h, y_i)] - E_{p(y,h|x_i)}[f(x_i, h, y)]$$

Step 2: Use online, stochastic gradient updates, for example i:

$$update_i = E_{p(y_i,h|x_i)}[f(x_i, h, y_i)] - E_{p(y,h|x_i)}[f(x_i, h, y)]$$

Step 3: Replace expectations with maxes (Viterbi approx.)

$$update_i = f(x_i, h', y_i) - f(x_i, h^*, y^*)$$ where

$y^*, h^* = \arg\max_{y,h} w \cdot f(x_i, h, y)$ and $h' = \arg\max_h w \cdot f(x_i, h, y_i)$

Hidden Variable Perceptron

Data: $\{(x_i, y_i) : i = 1 \ldots n\}$

For $t = 1 \ldots T :$ [iterate epochs]

For $i = 1 \ldots n$: [iterate examples]

$y^*, h^* \leftarrow \arg\max_{y,h} \langle \theta, \Phi(x_i, h, y) \rangle$ [predict]

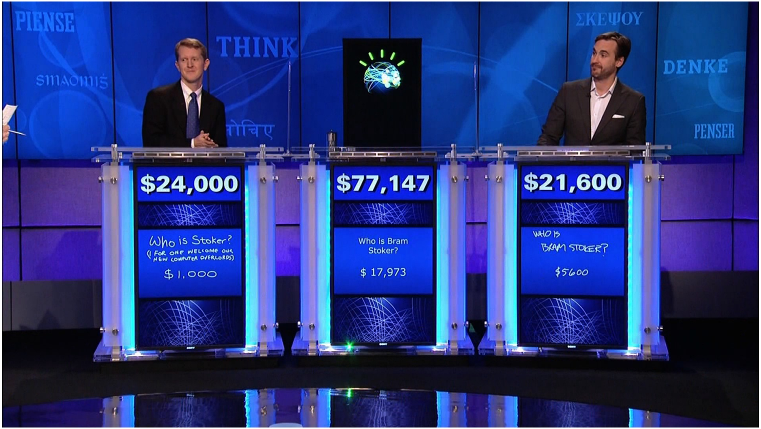
If $y^* \neq y_i$: [check]

$h' \leftarrow \arg\max_h \langle \theta, \Phi(x_i, h, y_i) \rangle$ [predict hidden]

$\theta \leftarrow \theta + \Phi(x_i, h', y_i) - \Phi(x_i, h^*, y^*)$ [update]

[Liang et al. 2006; Zettlemoyer and Collins 2007]

Contents


PIENSE
THINK
ΣΚΕΨΟΥ
DENKE
PENSER
$24,000
Who is Stoker?
(I FOR ONE WELCOME OUR NEW COMPUTER OVERLORDS)
$1,000
$77,147
Who is Bram Stoker?
$ 17,973
$21,600
WHO IS BRAM STOKER?
$5600

DeepQA

- Information Retrieval based factoid QA
- Combines search, rule-based extraction, and ranking
- Kitchen-sink type of approach
- (Nothing to do with deep learning)

DeepQA (Ferrucci, 2010)

- Massive parallelism: Exploit massive parallelism in the consideration of multiple interpretations and hypotheses.
- Many experts: Facilitate the integration, application, and contextual evaluation of a wide range of loosely coupled probabilistic question and content analytics.
- Pervasive confidence estimation: No component commits to an answer; all components produce features and associated confidences, scoring different question and content interpretations. An underlying confidence-processing substrate learns how to stack and combine the scores.
- Integrate shallow and deep knowledge: Balance the use of strict semantics and shallow semantics, leveraging many loosely formed ontologies

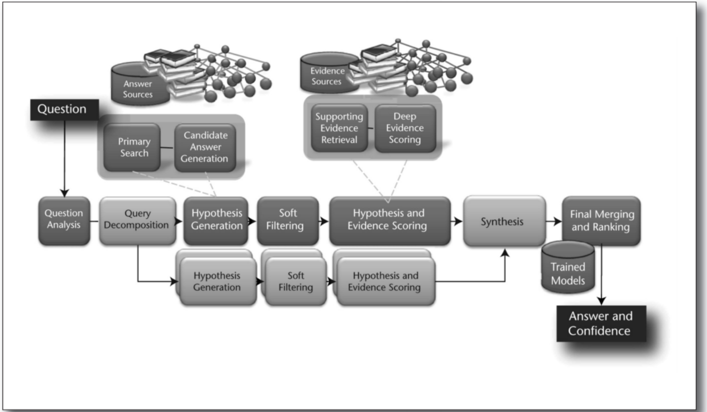


Figure 6. DeepQA High-Level Architecture.

This motivates an approach that merges answer scores before ranking and confidence estimation. Using an ensemble of matching, normalization, and coreference resolution algorithms, Watson identifies equivalent and related hypotheses (for example, Abraham Lincoln and Honest Abe) and then enables custom merging per feature to combine scores.

Given the kinds of questions and broad domain of the Jeopardy Challenge, the sources for Watson include a wide range of encyclopedias, dictionaries, thesauri, newswire articles, literary works, and so on.

A variety of search techniques are used, including the use of multiple text search engines with different underlying approaches (for example, Indri and Lucene), document search as well as passage search, knowledge base search using SPARQL on triple stores, the generation of multiple search queries for a single question, and backfilling hit lists to satisfy key constraints identified in the question.

Hypothesis Ranking

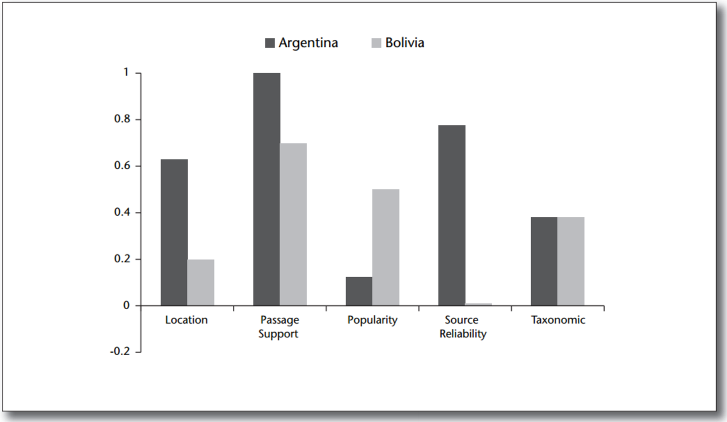


Figure 8. Evidence Profiles for Two Candidate Answers.

Dimensions are on the *x*-axis and relative strength is on the *y*-axis.

Other Aspects

- Parsing algorithm
- Inducing rules and parameters
- Relationship between syntax and semantics

CCG Categories

$$ADJ : \lambda x.fun(x)$$

- Basic building block
- Capture syntactic and semantic information jointly

CCG Categories

Syntax $ADJ : \lambda x.fun(x)$ Semantics

- Basic building block
- Capture syntactic and semantic information jointly

CCG Categories

Syntax $\boxed{ADJ} : \lambda x.fun(x)$

$$(S\backslash NP)/ADJ : \lambda f.\lambda x.f(x)$$

$$NP : CCG$$

- Primitive symbols: N, S, NP, ADJ and PP
- Syntactic combination operator (/,\)
- Slashes specify argument order and direction

CCG Categories

$$ADJ : \boxed{\lambda x.fun(x)}$$ Semantics

$$(S\backslash NP)/ADJ : \lambda f.\lambda x.f(x)$$

$$NP : CCG$$

- λ-calculus expression
- Syntactic type maps to semantic type

CCG Lexical Entries

$$\text{fun} \ \vdash ADJ : \lambda x.fun(x)$$

- Pair words and phrases with meaning
- Meaning captured by a CCG category

CCG Lexical Entries

$$\text{fun} \vdash ADJ : \lambda x.fun(x)$$

Natural Language

CCG Category

- Pair words and phrases with meaning
- Meaning captured by a CCG category