

# Learning Latent Programs for Question Answering

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ICLR

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# Goals

- Introduce a new challenge **task** for representation learning.

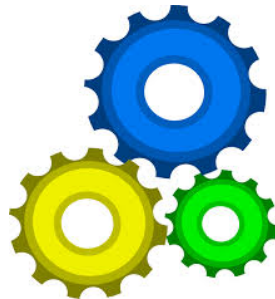


# Goals

- Introduce a new challenge **task** for representation learning.



- Show that **programs** are a compact and powerful representation.



# Outline

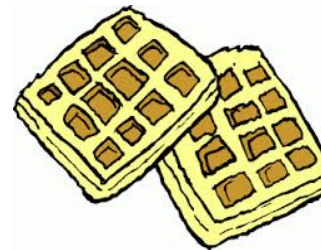
Question answering



Semantic parsing on tables

Year	Competition	Venue	Position	Event	Notes
Representing  Poland					
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			1st	Medley relay	1:50.46
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2009	Universiade	Belgrade, Serbia	2nd	4x400 m relay	3:05.69

Philosophical waffle





# Rule-based systems [1960-1980s]

*What is the average concentration of iron in ilmenite?*



```
(ING/BY
  (PUSH NP/ T
    (SETR SUBJ *)
    (TO VP/VP

      (* IF THE SUBJECT WAS NOT PROPERLY DETERMINED IN A
        POSS-ING COMPLEMENT, LOOK FOR IT HERE.)

    )))

(NP/
  (CAT DET T

    ((GETF POSSPRO                                (* START OF THE NP
                                                    NETWORK.))
      (ADDL ADJS (BUILDQ (POSS (NP (PRO *))))))
      (SETRQ DET THE

        (* IF THE DETERMINER IS A POSSESSIVE PRONOUN
          (MY, YOUR), CONSTRUCT THE POSSESSIVE MODIFIER AND USE
          'THE' FOR THE DETERMINER)

      )))

    (T (SETR DET *)))
    (TO NP/ART))
  (CAT PRO T
    (SETR N (BUILDQ (PRO *)))

    )
    (SETR NU (GETF NUMBER))
    (TO NP/NP))
  (MEM (WHETHER IF)
    T
    (SETR NTYPE *)
    (TO COMPL/NTYPE

      (* CONSTRUCT THE COMPLEMENT STRUCTURE FOR SENTENCES
        SUCH AS 'I DON'T KNOW WHETHER HE LEFT.')
```

# Retrieval-based QA [200s-]

*What company sells most greeting cards?*

Documents (web):

*...Hallmark remains the largest maker of greeting cards...*

# Retrieval-based QA [200s-]

*What company sells most greeting cards?*

Documents (web):

*...Hallmark remains the largest maker of greeting cards...*

- Question processing, document retrieval, answer extraction
- Rely on patterns, small set of question types, redundancy of web
- TREC competitions: 70% on factoid questions

# 1990s-: (statistical) semantic parsing

*What is the second largest city in California?*

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*What is the second largest city in California?*



semantic parsing

$\text{argmax}(\text{Type.City} \sqcap \text{ContainedBy.CA}, \text{Population})$

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*What is the second largest city in California?*



semantic parsing

$\text{argmax}(\text{Type.City} \sqcap \text{ContainedBy.CA}, \text{Population})$



execute

San Diego

- Zettlemoyer/Collins, 2005: CCG-based semantic parsing

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*What is the second largest city in California?*



semantic parsing



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- Liang et al., 2011: train from question-answer pairs

# 1990s-: (statistical) semantic parsing

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semantic parsing



execute

San Diego

- Zettlemoyer/Collins, 2005: CCG-based semantic parsing
- Liang et al., 2011: train from question-answer pairs
- Berant et al., 2013, Kwiatkowski et al., 2013: on Freebase



# Question answering on



WebQuestions dataset (6K questions) [Berant et al., 2013]

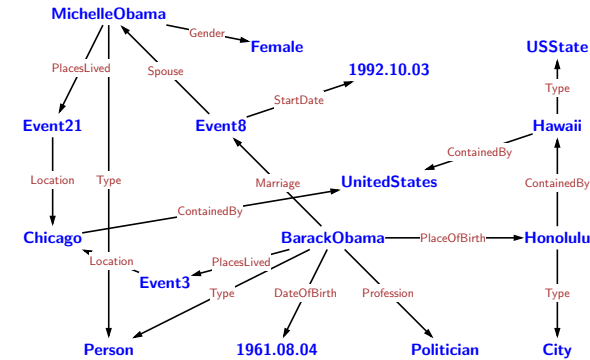
*what art did wassily kandinsky do?*

*what boarding school did mark zuckerberg go to?*

*what book is mark twain famous for?*

*what did george washington carver made?*

*through which countries of the sahel does the niger river flow?*



# Question answering on



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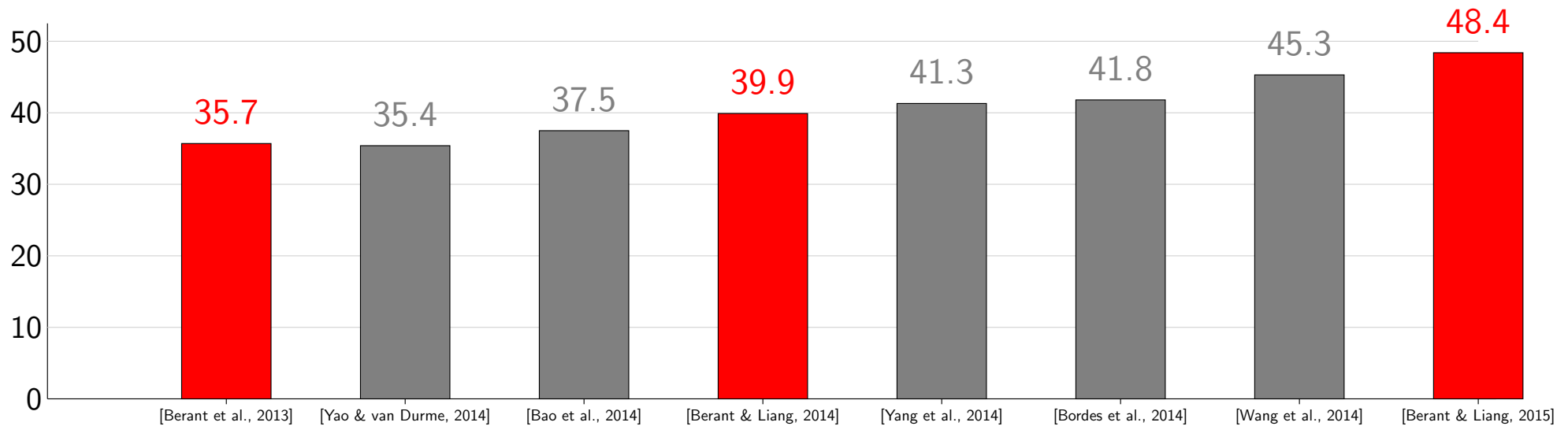
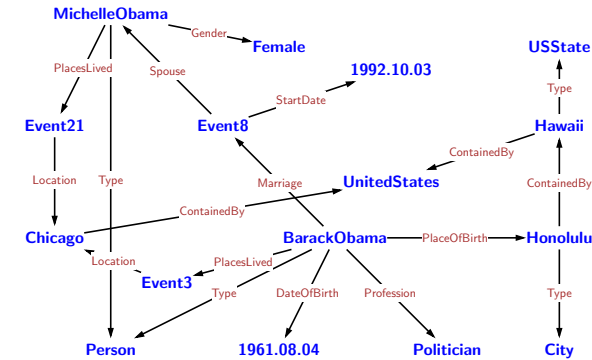
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# What's next?

## 1. Breadth: answer from less structured knowledge sources



database  
(structured)



knowledge base  
(structured)



Year	Competition	Venue	Position	Event	Notes
2001	World Youth Championships	Debrecen, Hungary	2nd	400 m	47.12
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2006	World Indoor Championships	Moscow, Russia	1st	4x400 m relay	3:04.41
	European Championships	Göteborg, Sweden	7th	400 m	46.99
2007	European Indoor Championships	Birmingham, United Kingdom	2nd (F)	4x400 m relay	3:02.53
	Universiade	Bangkok, Thailand	2nd (F)	4x400 m relay	3:06.10
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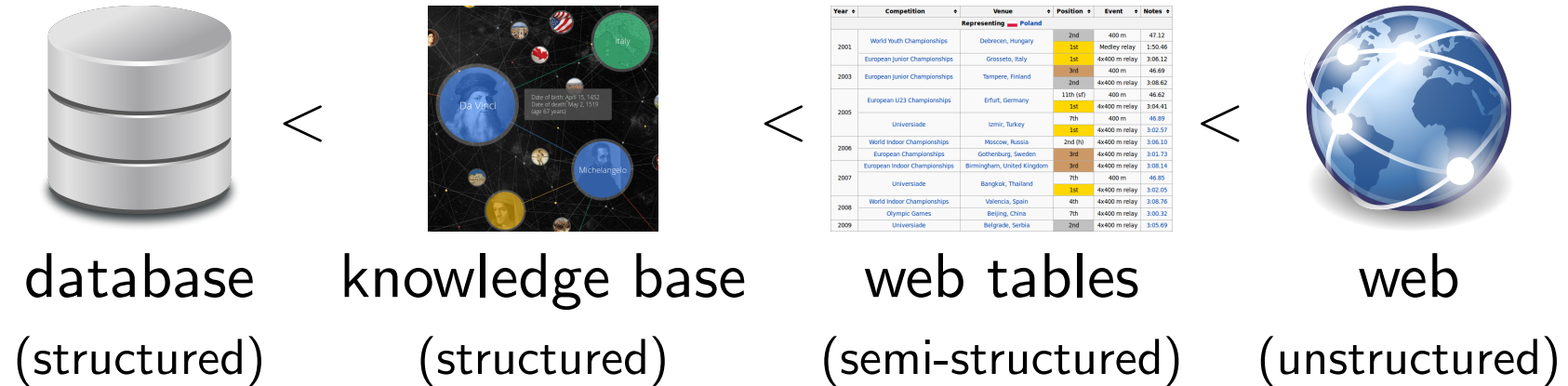
web tables  
(semi-structured)



web  
(unstructured)

# What's next?

1. **Breadth:** answer from less structured knowledge sources



2. **Depth:** handle compositional language

*Where was Barack Obama born?* < *How many presidents after Abraham Lincoln were born in Ohio?*

# Outline

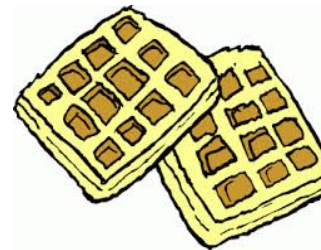
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Philosophical waffle




# Semantic parsing on tables [ACL 2015]



Panupong (Ice) Pasupat

Year ↕	Competition ↕	Venue ↕	Position ↕	Event ↕	Notes ↕
<b>Representing  Poland</b>					
2001	World Youth Championships	Debrecen, Hungary	2nd	400 m	47.12
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*In what city did Piotr's last 1st place finish occur?*

Year ↕	Competition ↕	Venue ↕	Position ↕	Event ↕	Notes ↕
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			European Championships	Gothenburg, Sweden	3rd
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*How long did it take this competitor to finish the 4x400 meter relay at Universiade in 2005?*



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*Where was the competition held immediately before the one in Turkey?*

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*How many times has this competitor placed 5th or better in competition?*

# Dataset

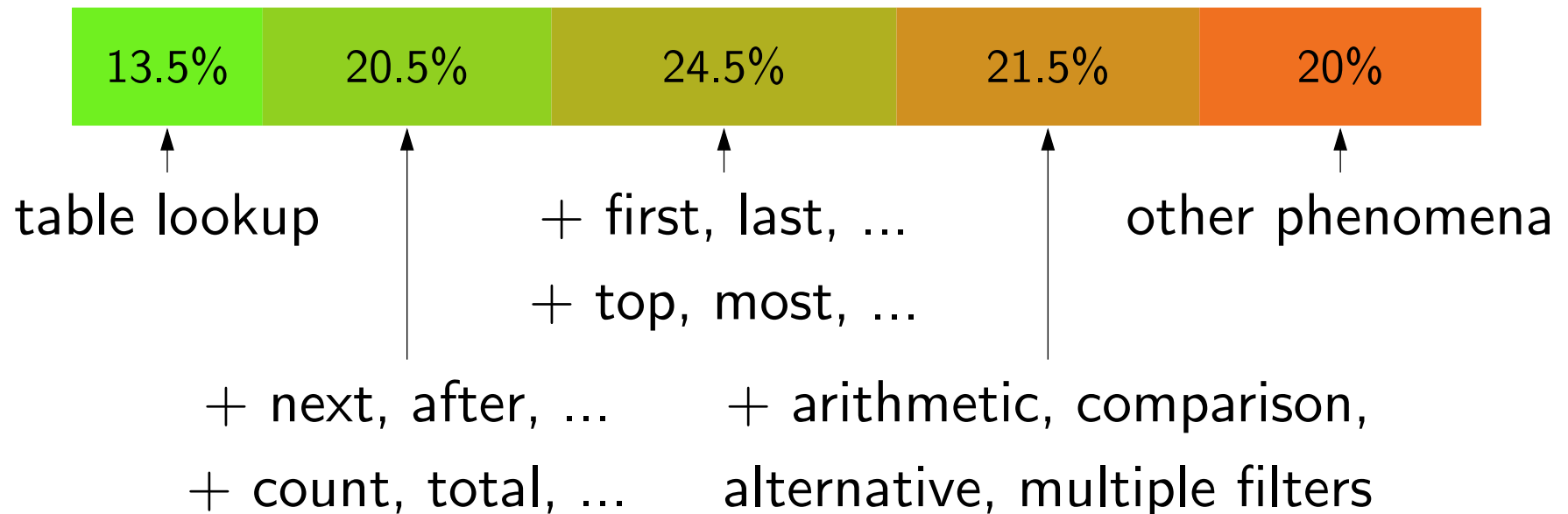
## WikiTableQuestions (2108 tables, 22033 questions)

- **3929** unique column headers = relations
- **Breadth:** Freebase can answer only  $\approx 20\%$  of the questions
- Tables in test data are **not seen** during training

# Dataset

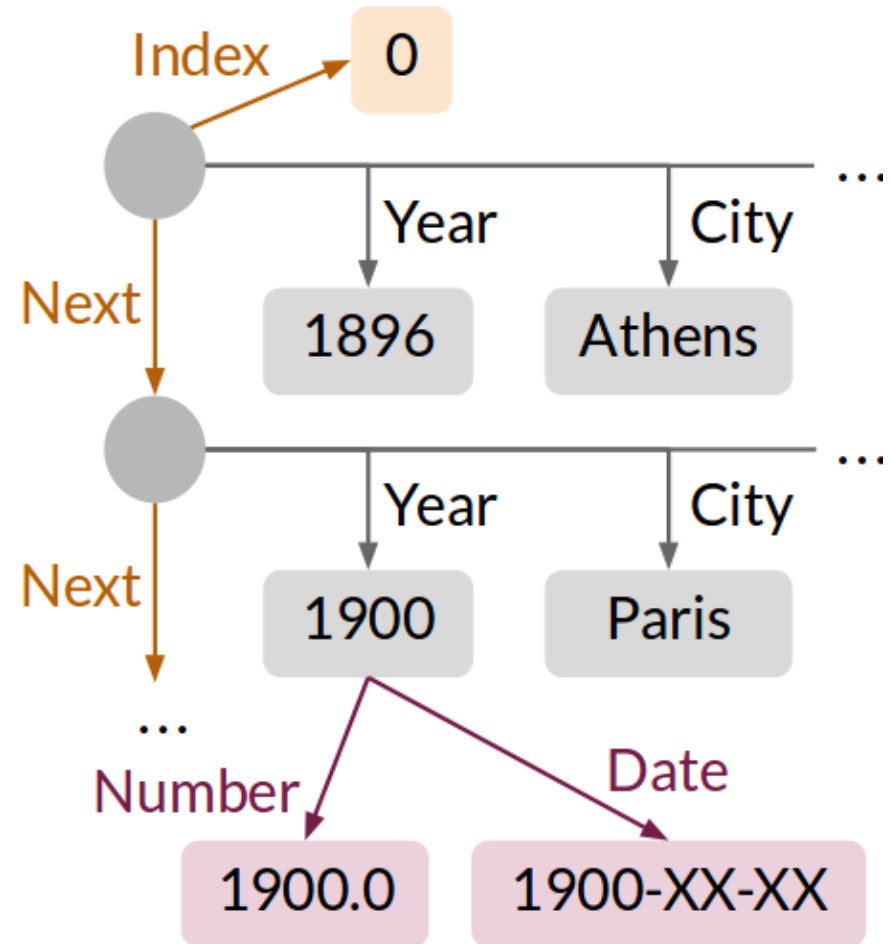
## WikiTableQuestions (2108 tables, 22033 questions)

- **3929** unique column headers = relations
- **Breadth:** Freebase can answer only  $\approx 20\%$  of the questions
- Tables in test data are **not seen** during training
- **Depth:** crowdsourced complex questions



# Graph representation

Year	City	Country	Nations
1896	Athens	Greece	14
1900	Paris	France	24
1904	St. Louis	USA	12
...	...	...	...
2004	Athens	Greece	201
2008	Beijing	China	204
2012	London	UK	204



Add normalization / auxiliary edges (custom functions), push resolution to semantic parsing

# Lambda DCS logical forms

Entity

Chicago

# Lambda DCS logical forms

Entity

Chicago

Join

PlaceOfBirth.Chicago

# Lambda DCS logical forms

Entity

Chicago

Join

PlaceOfBirth.Chicago

Intersect

Type.Person  $\sqcap$  PlaceOfBirth.Chicago



# Lambda DCS logical forms

Entity

Chicago

Join

PlaceOfBirth.Chicago

Intersect

Type.Person  $\sqcap$  PlaceOfBirth.Chicago

Aggregation

count(Type.Person  $\sqcap$  PlaceOfBirth.Chicago)

# Lambda DCS logical forms

Entity

Chicago

Join

PlaceOfBirth.Chicago

Intersect

Type.Person  $\sqcap$  PlaceOfBirth.Chicago

Aggregation

count(Type.Person  $\sqcap$  PlaceOfBirth.Chicago)

Superlative

argmin(Type.Person  $\sqcap$  PlaceOfBirth.Chicago, DateOfBirth)

# Lambda DCS logical forms

Entity

Chicago

Join

PlaceOfBirth.Chicago

Intersect

Type.Person  $\sqcap$  PlaceOfBirth.Chicago

Aggregation

count(Type.Person  $\sqcap$  PlaceOfBirth.Chicago)

Superlative

argmin(Type.Person  $\sqcap$  PlaceOfBirth.Chicago, DateOfBirth)

Anaphora

$\mu x$ . Type.Person  $\sqcap$  Children.Influence. $x$

# Lambda DCS logical forms

## Entity

Chicago

## Join

PlaceOfBirth.Chicago

## Intersect

Type.Person  $\sqcap$  PlaceOfBirth.Chicago

## Aggregation

count(Type.Person  $\sqcap$  PlaceOfBirth.Chicago)

## Superlative

argmin(Type.Person  $\sqcap$  PlaceOfBirth.Chicago, DateOfBirth)

## Anaphora

$\mu x$ . Type.Person  $\sqcap$  Children.Influence. $x$

## Variable

argmax(Type.Person,  $\mathbf{R}[\lambda x$ .count(Parent.Parent. $x$ )])

# Training algorithm

*Where did Mozart tupress?*

**Vienna**

# Training algorithm

*Where did Mozart tupress?*

PlaceOfBirth.WolfgangMozart

PlaceOfDeath.WolfgangMozart

PlaceOfMarriage.WolfgangMozart

**Vienna**

# Training algorithm

*Where did Mozart tupress?*

PlaceOfBirth.WolfgangMozart ⇒ Salzburg

PlaceOfDeath.WolfgangMozart ⇒ Vienna

PlaceOfMarriage.WolfgangMozart ⇒ Vienna

**Vienna**

# Training algorithm

*Where did Mozart tupsress?*

~~PlaceOfBirth.WolfgangMozart → Salzburg~~

PlaceOfDeath.WolfgangMozart ⇒ Vienna

PlaceOfMarriage.WolfgangMozart ⇒ Vienna

**Vienna**



# Training algorithm

*Where did Mozart tupress?*

~~PlaceOfBirth.WolfgangMozart → Salzburg~~

PlaceOfDeath.WolfgangMozart ⇒ Vienna

PlaceOfMarriage.WolfgangMozart ⇒ Vienna

**Vienna**

*Where did Hogarth tupress?*

# Training algorithm

*Where did Mozart tupress?*

~~PlaceOfBirth.WolfgangMozart → Salzburg~~

PlaceOfDeath.WolfgangMozart ⇒ Vienna

PlaceOfMarriage.WolfgangMozart ⇒ Vienna

**Vienna**

*Where did Hogarth tupress?*

PlaceOfBirth.WilliamHogarth

PlaceOfDeath.WilliamHogarth

PlaceOfMarriage.WilliamHogarth

**London**

# Training algorithm

*Where did Mozart tupress?*

~~PlaceOfBirth.WolfgangMozart → Salzburg~~

PlaceOfDeath.WolfgangMozart ⇒ Vienna

PlaceOfMarriage.WolfgangMozart ⇒ Vienna

**Vienna**

*Where did Hogarth tupress?*

PlaceOfBirth.WilliamHogarth ⇒ London

PlaceOfDeath.WilliamHogarth ⇒ London

PlaceOfMarriage.WilliamHogarth ⇒ Paddington

**London**

# Training algorithm

*Where did Mozart tupress?*

~~PlaceOfBirth.WolfgangMozart → Salzburg~~

PlaceOfDeath.WolfgangMozart ⇒ Vienna

PlaceOfMarriage.WolfgangMozart ⇒ Vienna

**Vienna**

*Where did Hogarth tupress?*

PlaceOfBirth.WilliamHogarth ⇒ London

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# Training algorithm

*Where did Mozart tupress?*

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**London**

# Parsing/generation

*Greece held its last Summer Olympics in which year?*

?

2004

Year	City	Country	Nations
1896	Athens	Greece	14
1900	Paris	France	24
1904	St. Louis	USA	12
...	...	...	...
2004	Athens	Greece	201
2008	Beijing	China	204
2012	London	UK	204

# Parsing/generation

*Greece held its last Summer Olympics in which year?*

**R[Index].Country.Greece**

2004

Year	City	Country	Nations
1896	Athens	Greece	14
1900	Paris	France	24
1904	St. Louis	USA	12
...	...	...	...
2004	Athens	Greece	201
2008	Beijing	China	204
2012	London	UK	204

# Parsing/generation

*Greece held its last Summer Olympics in which year?*

**R[Nations].Country.Greece**

2004

Year	City	Country	Nations
1896	Athens	Greece	14
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1904	St. Louis	USA	12
...	...	...	...
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# Parsing/generation

*Greece held its last Summer Olympics in which year?*

argmax(Country.Greece, Nations)

2004

Year	City	Country	Nations
1896	Athens	Greece	14
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...	...	...	...
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# Parsing/generation

*Greece held its last Summer Olympics in which year?*

$\text{argmax}(\text{Country.Greece, Index})$

2004

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# Parsing/generation

*Greece held its last Summer Olympics in which year?*

... (hundreds of logical forms later) ...

2004

Year	City	Country	Nations
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# Parsing/generation

*Greece held its last Summer Olympics in which year?*

**R[Date].R[Year].argmax(Country.Greece, Index)**

2004

Year	City	Country	Nations
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# Parsing/generation

*Greece held its last Summer Olympics in which year?*

```
R[Date].R[Year].R[Prev].R[Prev].argmax(Type.Row, Index)
```

2004

Year	City	Country	Nations
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$x$ : *Greece held its last Summer Olympics in which year?*

$z$ :  $\mathbf{R}[\text{Date}].\mathbf{R}[\text{Year}].\text{argmax}(\text{Country.Greece}, \text{Index})$

$y$ : 2004

Feature vector  $\phi(x, z) \in \mathbb{R}^F$ :



$x$ : *Greece held its last Summer Olympics in which year?*

$z$ :  $\mathbf{R}[\text{Date}].\mathbf{R}[\text{Year}].\text{argmax}(\text{Country.Greece}, \text{Index})$

$y$ : 2004

Feature vector  $\phi(x, z) \in \mathbb{R}^F$ :

Feature template	Feature	Value
(word, predicate)	( <i>Greece</i> , <i>Greece</i> )	1
	( <i>held</i> , <i>Greece</i> )	1
	( <i>its</i> , <i>Greece</i> )	1
	( <i>Greece</i> , <i>argmax</i> )	1
	phrase=predicate	1
	...	...
(missing predicates)	missing	1
	...	...
(denotation size)	size=1	1
(phrase, denotation type)	( <i>which</i> , <i>Date</i> )	1
	( <i>which year</i> , <i>Date</i> )	1
	( <i>in which</i> , <i>Date</i> )	1
	...	...

# Modeling logical forms

Scoring function:

$$\text{Score}_\theta(x, z) = \phi(x, z) \cdot \theta$$

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Model:

$$p_\theta(z \mid x) = \frac{\exp(\text{Score}_\theta(x, z))}{\sum_{z' \in \mathcal{Z}(x)} \exp(\text{Score}_\theta(x, z'))}$$

# Learning

Training data:

*What's Bulgaria's capital?*

Sofia

*What movies has Tom Cruise been in?*

TopGun, VanillaSky,...

...

+grammar, +features

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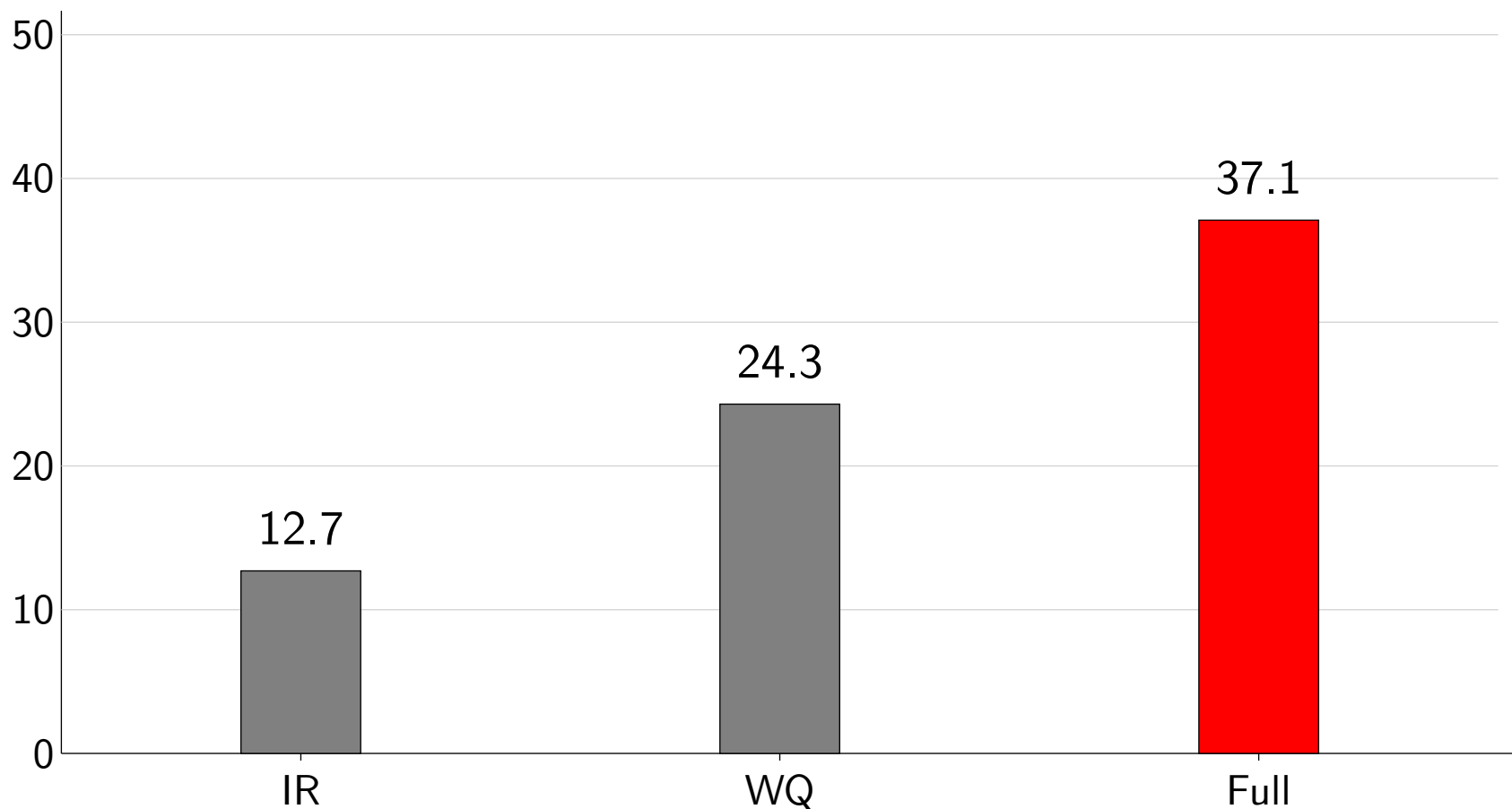
Setup:

AdaGrad (3 iterations), beam search (200)  $\Rightarrow$  10 hours

# Results

IR: Train classifier to pick answer directly from table.

WQ: Use logical complexity of Freebase work.



# Right for the wrong reasons

*How many times did Greece hold the Summer Olympics?*

```
count(Country.Greece)
```

2



# Right for the wrong reasons

*How many times did Greece hold the Summer Olympics?*

`count(Country.Greece) – count(Country.Norway)`

2

# Right for the wrong reasons

*How many times did Greece hold the Summer Olympics?*

**`R[Index].R[Next].R[Next].argmin(Country.Greece, Index)`**

2

# Right for the wrong reasons

*How many times did Greece hold the Summer Olympics?*

**R[Index].R[Next].R[Next].argmin(Country.Greece, Index)**

2

Can get right answer: 76.6%

Can get right logical form: 53.5%

# Examples of correct predictions

*What train was developed after the erlangener erprobungstrager?*

*According to the table, what is the last title that spicy horse produced?*

*Who finished directly after the driver who finished in 1:28.745?*

*Which album has the highest number of sales but doesn't have a designated artist?*

*How many districts have a population density of at least 1000.0?*

# Examples of errors

Unhandled operations (19%):

- *Was there more gold medals won than silver?*
- *Which movies were number 1 for at least two **consecutive** weeks?*
- *How many titles had the **same** author listed as the illustrator?*

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Lexical mismatch:

- *Mexican* ⇒ Mexico, *airplane* ⇒ Model

# Paradigm

*[utterance: user input]*



semantic parsing

[program]



execute

[denotation: user output]



# Paradigm

*[utterance: user input]*



semantic parsing

[program]



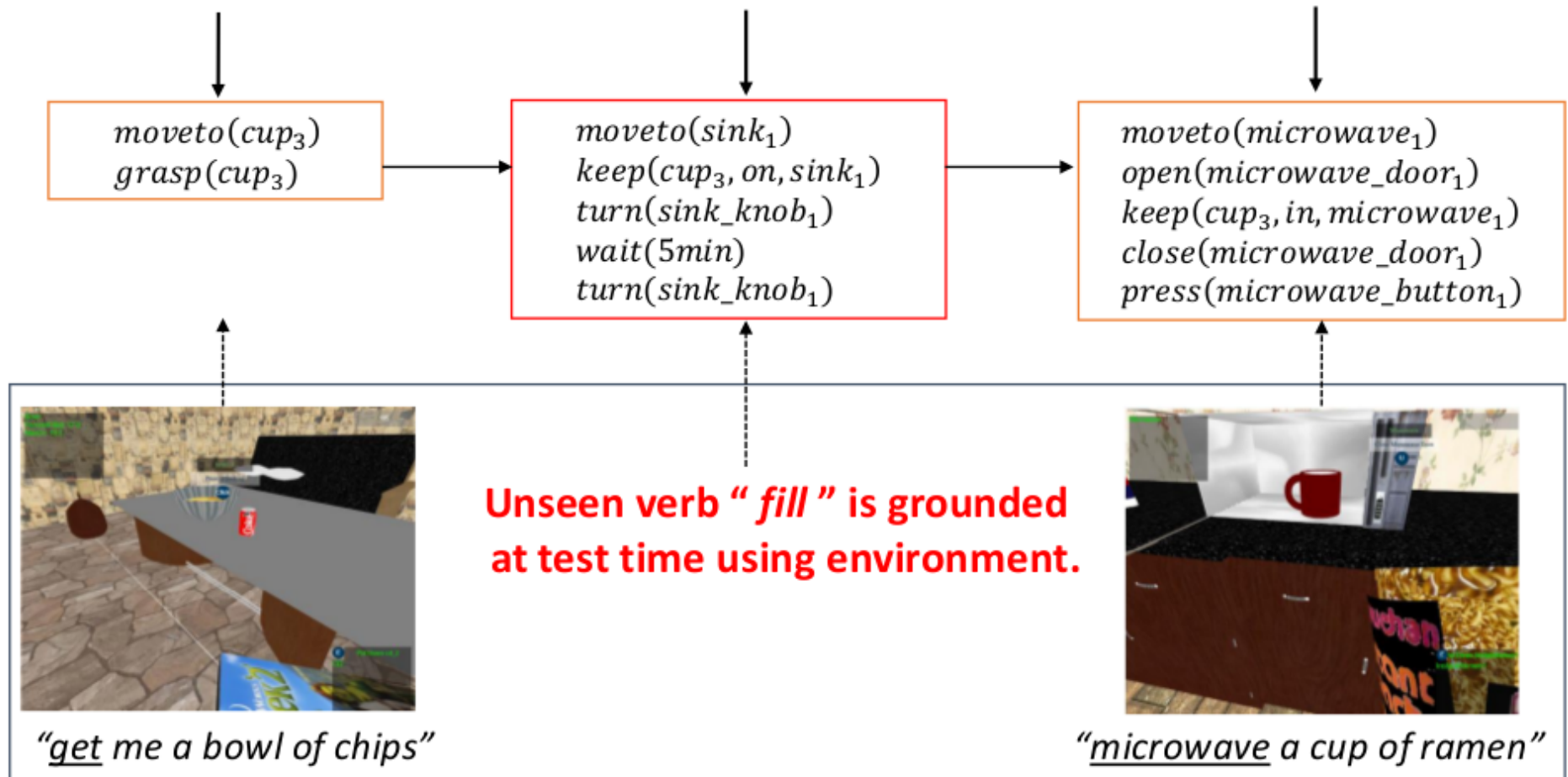
execute

[denotation: user output]

**Induce hidden program to accomplish end goal**

# Interpreting high-level instructions

**Text:** “get the cup, fill it with water and then microwave the cup”



Lexicon  $\Lambda$  from training

# Outline

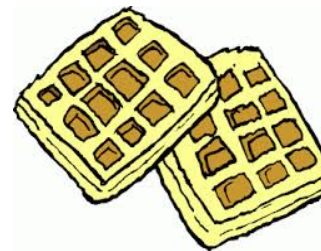
Question answering



Semantic parsing on tables

Year	Competition	Venue	Position	Event	Notes
Representing  Poland					
2001	World Youth Championships	Debrecen, Hungary	2nd	400 m	47.12
			1st	Medley relay	1:50.46
	European Junior Championships	Grosseto, Italy	1st	4x400 m relay	3:06.12
2003	European Junior Championships	Tampere, Finland	3rd	400 m	46.69
			2nd	4x400 m relay	3:08.62
2005	European U23 Championships	Erfurt, Germany	11th (sf)	400 m	46.62
			1st	4x400 m relay	3:04.41
			7th	400 m	46.89
	Universiade	Izmir, Turkey	1st	4x400 m relay	3:02.57
2006	World Indoor Championships	Moscow, Russia	2nd (h)	4x400 m relay	3:06.10
	European Championships	Gothenburg, Sweden	3rd	4x400 m relay	3:01.73
	European Indoor Championships	Birmingham, United Kingdom	3rd	4x400 m relay	3:08.14
2007	Universiade	Bangkok, Thailand	7th	400 m	46.85
			1st	4x400 m relay	3:02.05
2008	World Indoor Championships	Valencia, Spain	4th	4x400 m relay	3:08.76
	Olympic Games	Beijing, China	7th	4x400 m relay	3:00.32
2009	Universiade	Belgrade, Serbia	2nd	4x400 m relay	3:05.69

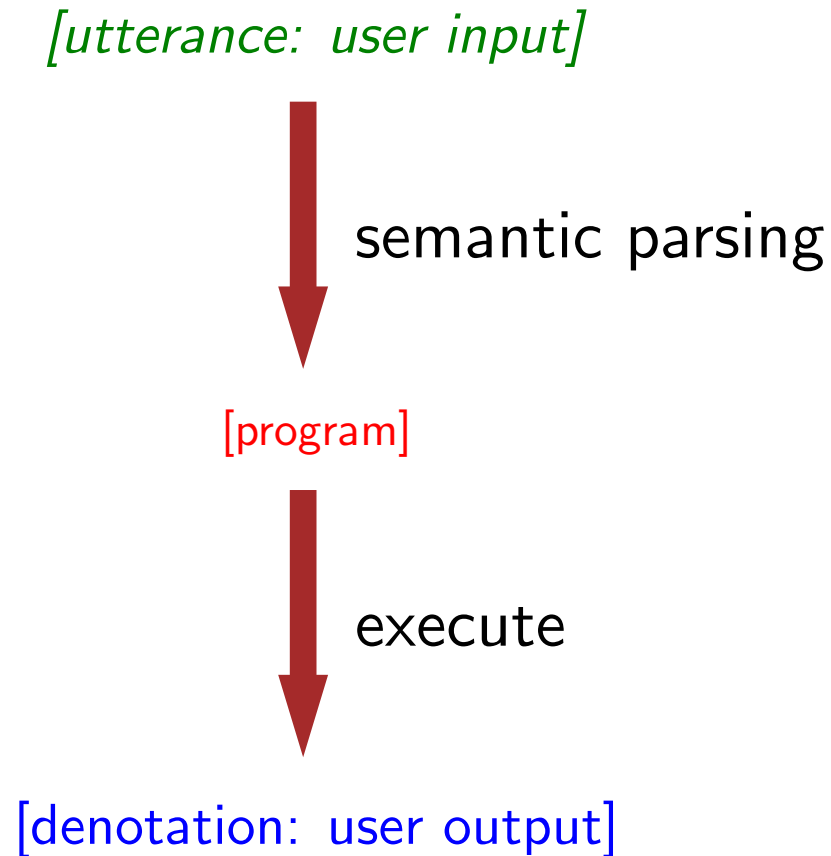
Philosophical waffle



# Point 1: deep learning?

*Deep learning ... attempt to model high-level abstractions in data by using model architectures, with complex structures or otherwise, composed of multiple non-linear transformations. — Wikipedia*

# Point 1: deep learning?



# Point 1: deep learning?

*[utterance: user input]*



semantic parsing

[program]



execute

*[denotation: user output]*

matrix-vector products  $\Rightarrow$  argmax, count, intersection

**Weakness:** can't represent fuzzy concepts as easily

**Strength:** powerful operations (argmax)

## Point 2: representation?

*It is raining outside.*

*There are at least two people in this room.*

What is the "type" of a sentence?

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What is the "type" of a sentence?

~~Bool~~

World  $\rightarrow$  Bool

If represent sentence as vector/matrix/tensor, it needs to act as a function.

# Model-theoretic semantics

Factorization: **understanding** and **knowing**

*What is the second largest city in California?*

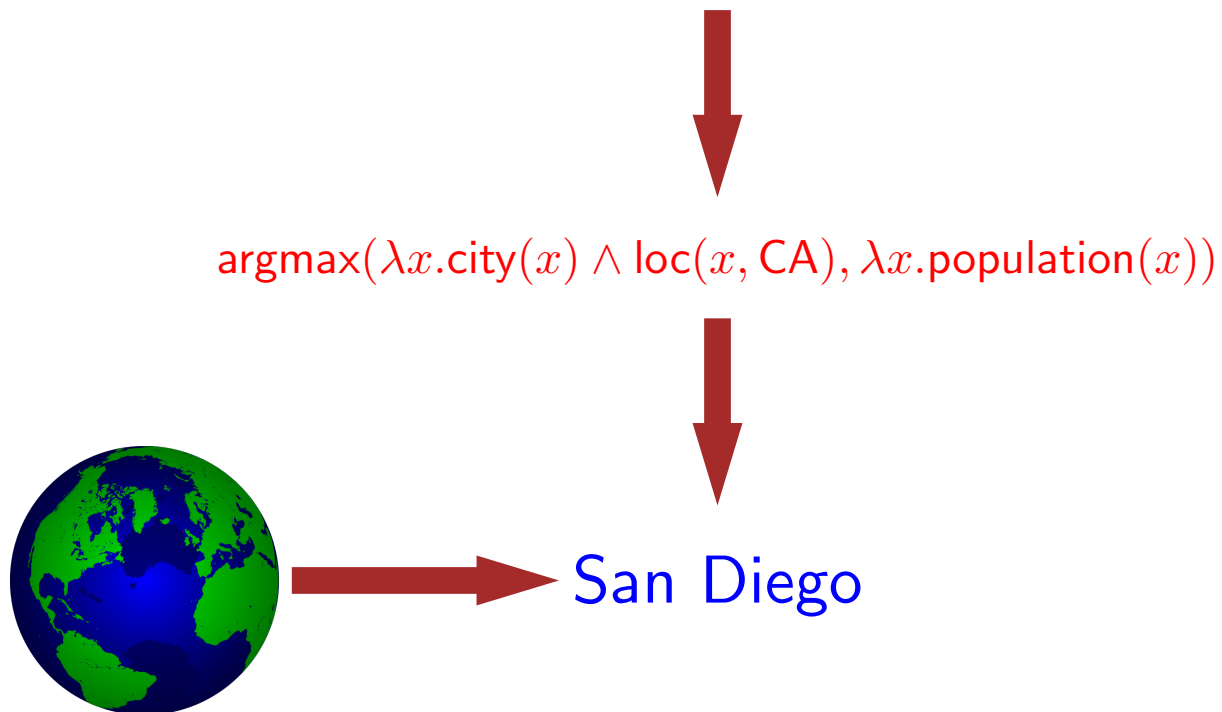


$\text{argmax}(\lambda x.\text{city}(x) \wedge \text{loc}(x, \text{CA}), \lambda x.\text{population}(x))$

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## Point 3: amount of data

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Of course, there is a lot of unlabeled data...

But sometimes, there is **no data**...how to even start?

# Overnight semantic parsing

Domain



# Overnight semantic parsing

Domain

↓ (1) by builder (~30 minutes)

**Seed lexicon**

article	→ TypeNP[article]
publication date	→ RelNP[publicationDate]
cites	→ VP/NP[cites]
	...

# Overnight semantic parsing

Domain

↓ (1) by builder (~30 minutes)

## Seed lexicon

article → TypeNP[article]  
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...

↓ (2) via domain-general grammar

## Logical forms and canonical utterances

*article with the largest publication date*

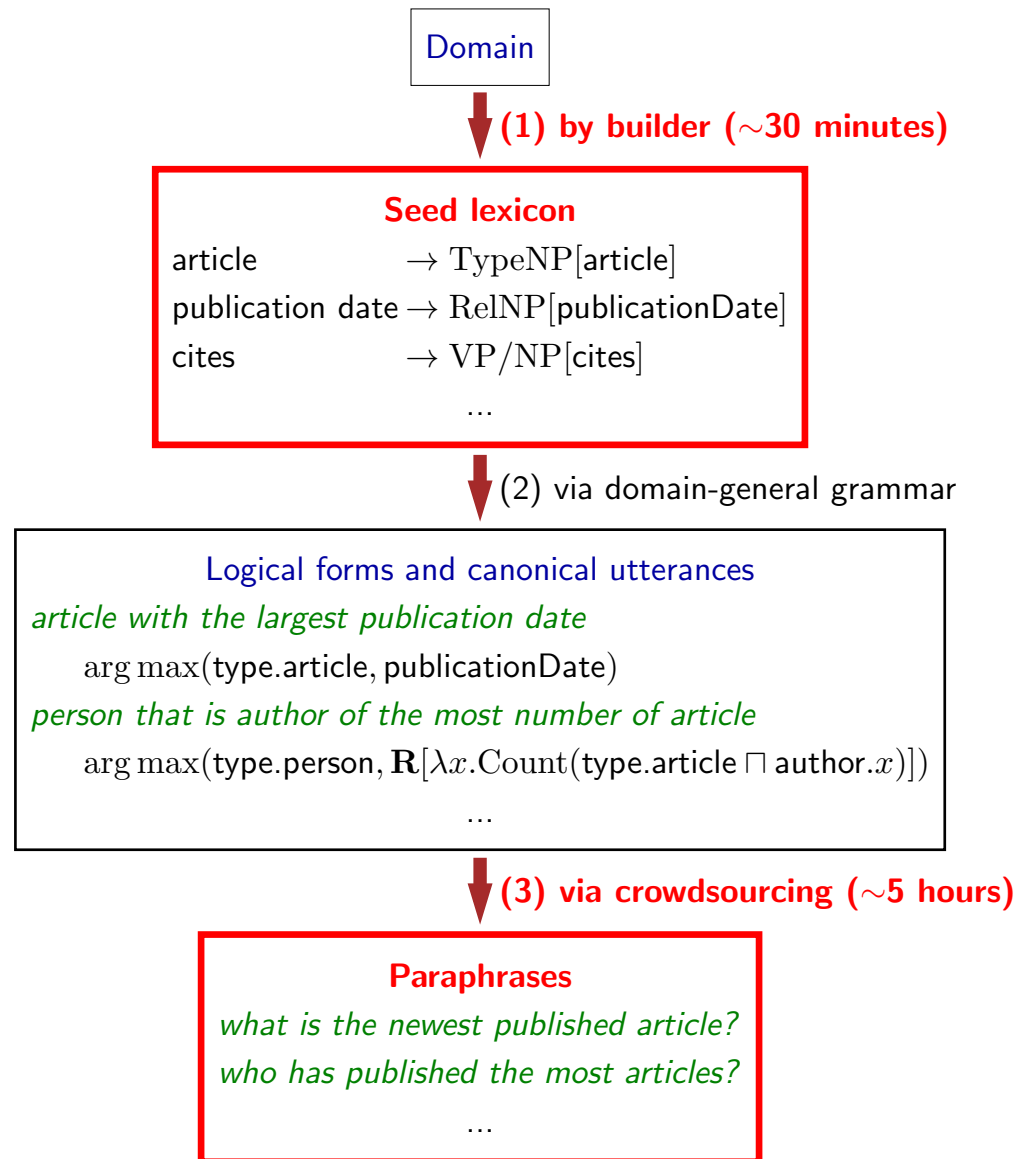
$\text{arg max}(\text{type.article}, \text{publicationDate})$

*person that is author of the most number of article*

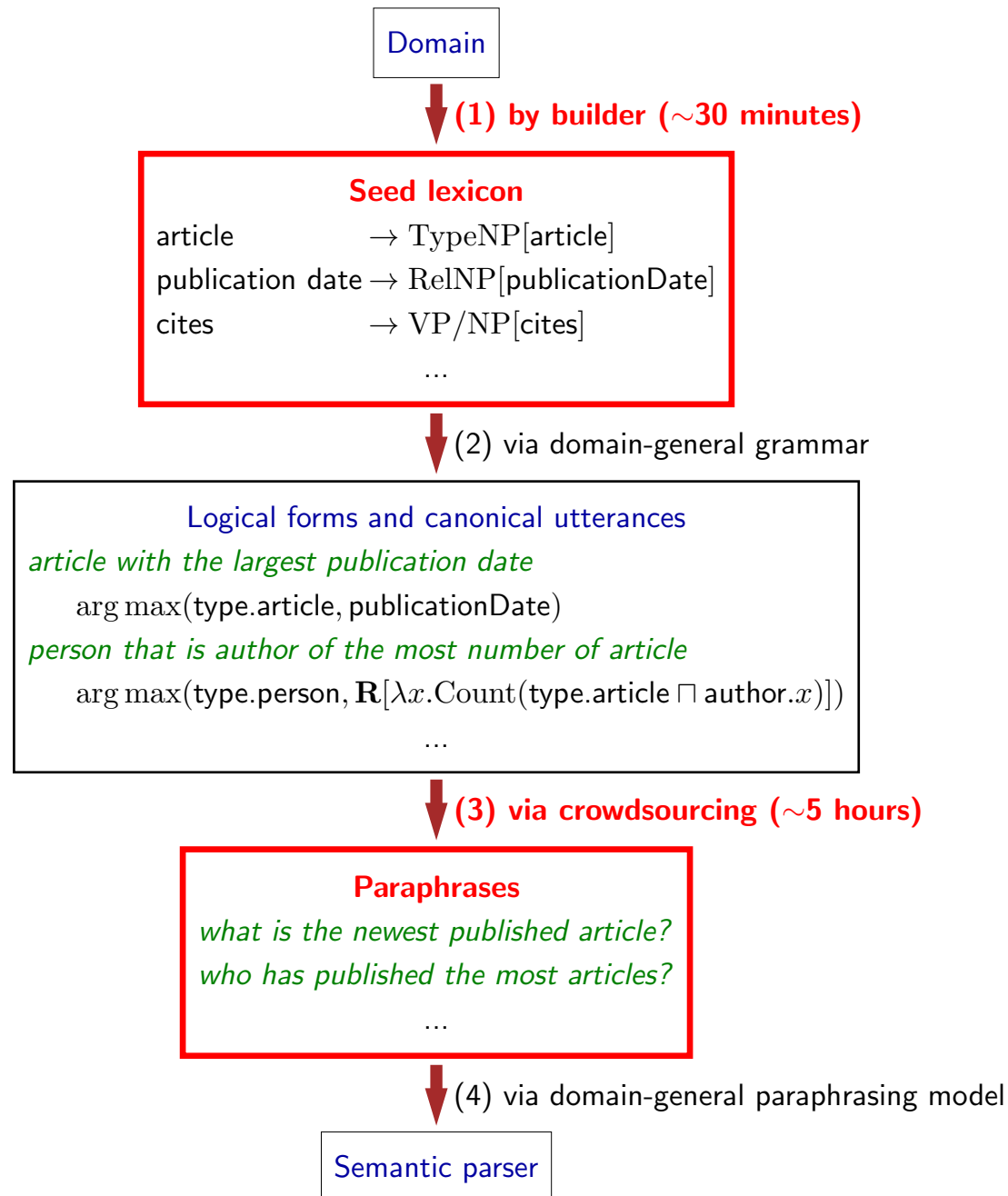
$\text{arg max}(\text{type.person}, \mathbf{R}[\lambda x. \text{Count}(\text{type.article} \sqcap \text{author}.x)])$

...

# Overnight semantic parsing



# Overnight semantic parsing



# Open challenges

- **Prediction:** multiple steps of computation/reasoning



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- **Prediction:** multiple steps of computation/reasoning



- **Training:** needle in a haystack supervision (with rusty nails) — delayed rewards in RL



# Learning representations

Can we use RNNs/LSTMs to map utterances to logical forms?

Can we redefine the semantics of logical forms using vector spaces?

Can memory networks/neural Turing machines learn to answer complex questions?

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Can we use RNNs/LSTMs to map utterances to logical forms?

Can we redefine the semantics of logical forms using vector spaces?

Can memory networks/neural Turing machines learn to answer complex questions?

**Think objectively about the computation a representation offers**



# Goals

- Introduce a new challenge **task** for representation learning.

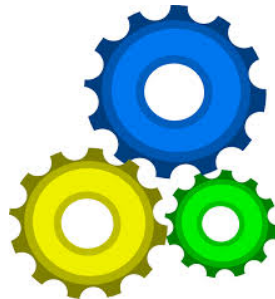


# Goals

- Introduce a new challenge **task** for representation learning.



- Show that **programs** are a compact and powerful representation.



## Code and data

<http://www-nlp.stanford.edu/software/sempr/>

<http://www.codalab.org>

## Funding

Google

Microsoft

DARPA

**Thank you!**