Scaling Semantic Parsers with On-the-Fly Ontology Matching

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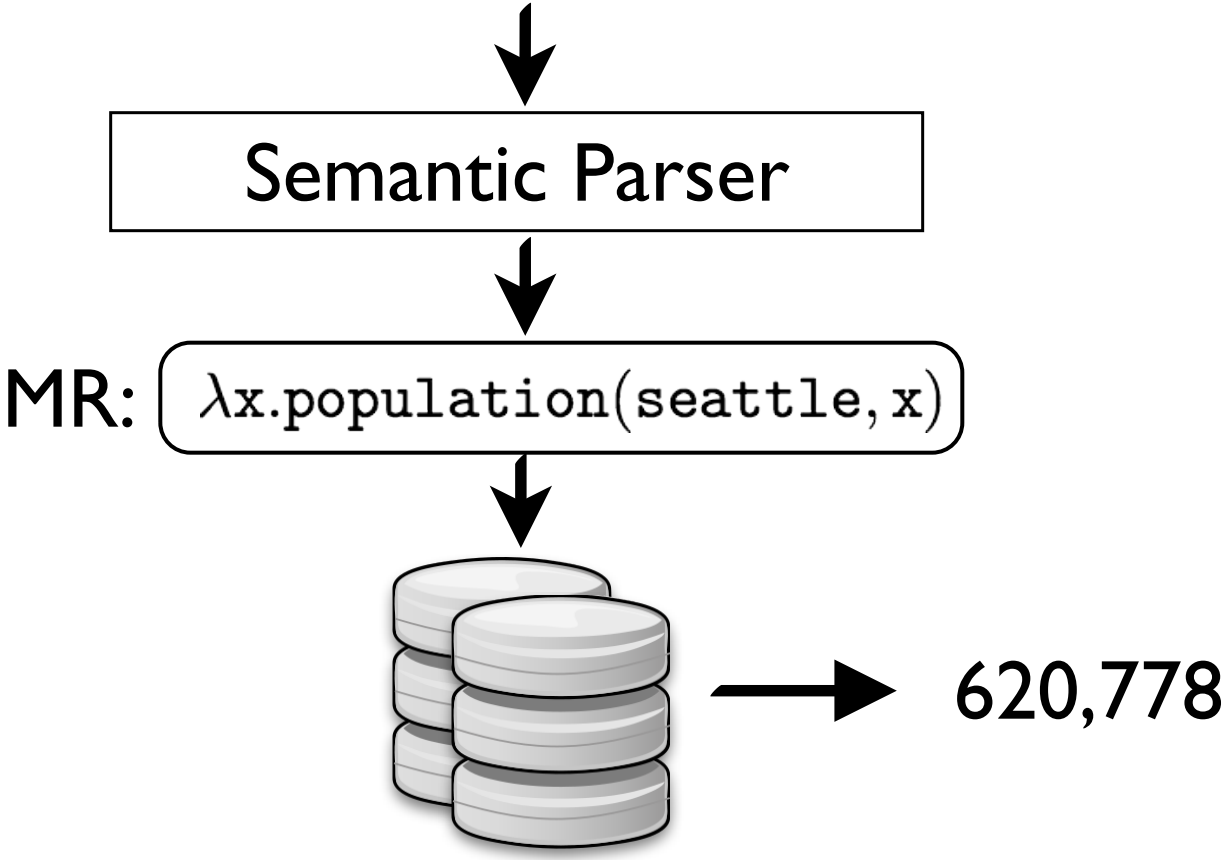
Semantic Parsing

Q: How many people live in Seattle?



Open Domain QA

Q Who managed Liverpool F.C. from 2004 to june 2010?

A Rafael Benitez

Q What architectural style is the Brooklyn Bridge?

A Gothic Revival architecture

Q What are the symptoms of prostate cancer?

A {Hematuria, Nocturia, Dysuria, ... }

Q How many people ride the monorail in Seattle daily?

A 7,000

Open Domain QA

Q Who managed Liverpool FC from 2004 to june 2010?

A

Q

A

Q

A

Q

A 7,000

Freebase is a community authored knowledge base with:

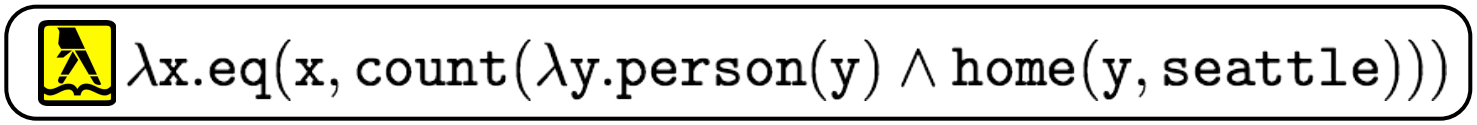
- 40 Million Entities
- 2 Billion Facts
- 20,000 Relations
- 10,000 Types
- 100 Domains

Query is Domain Dependent

How many people live in Seattle?

Query is Domain Dependent

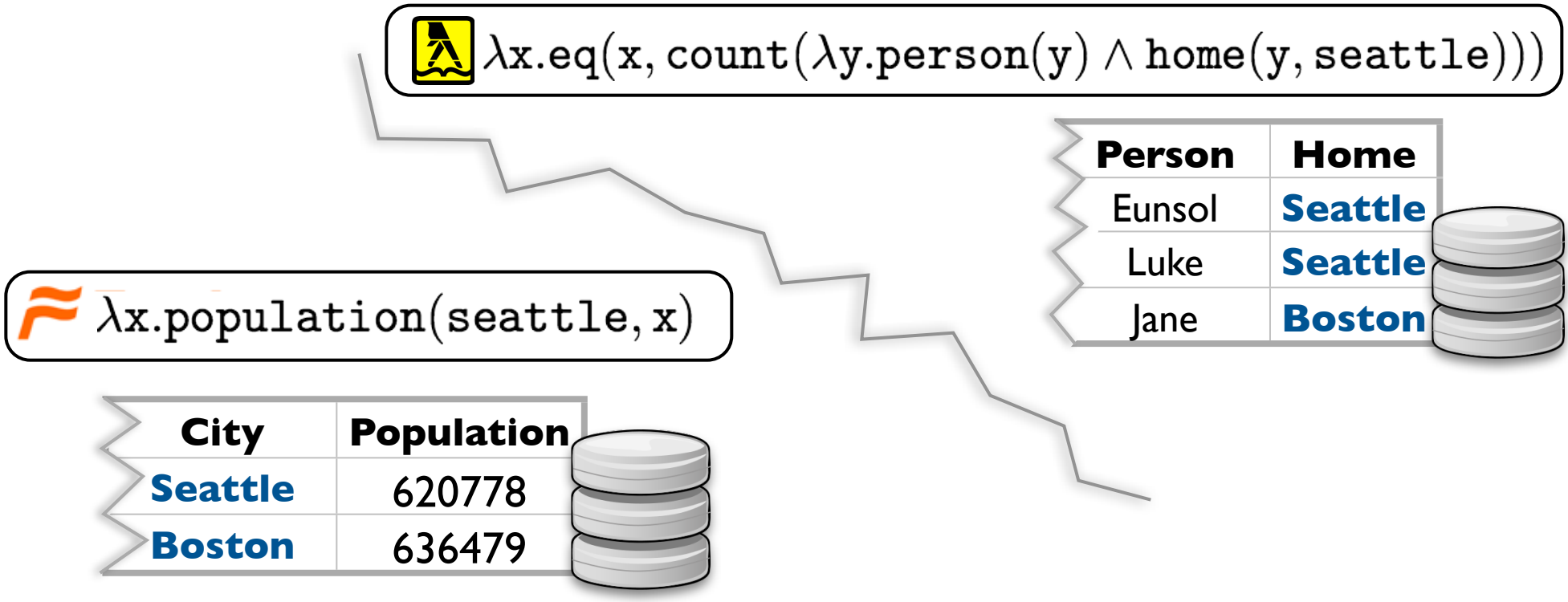
How many people live in Seattle?



Person	Home
Eunsol	Seattle
Luke	Seattle
Jane	Boston

Query is Domain Dependent

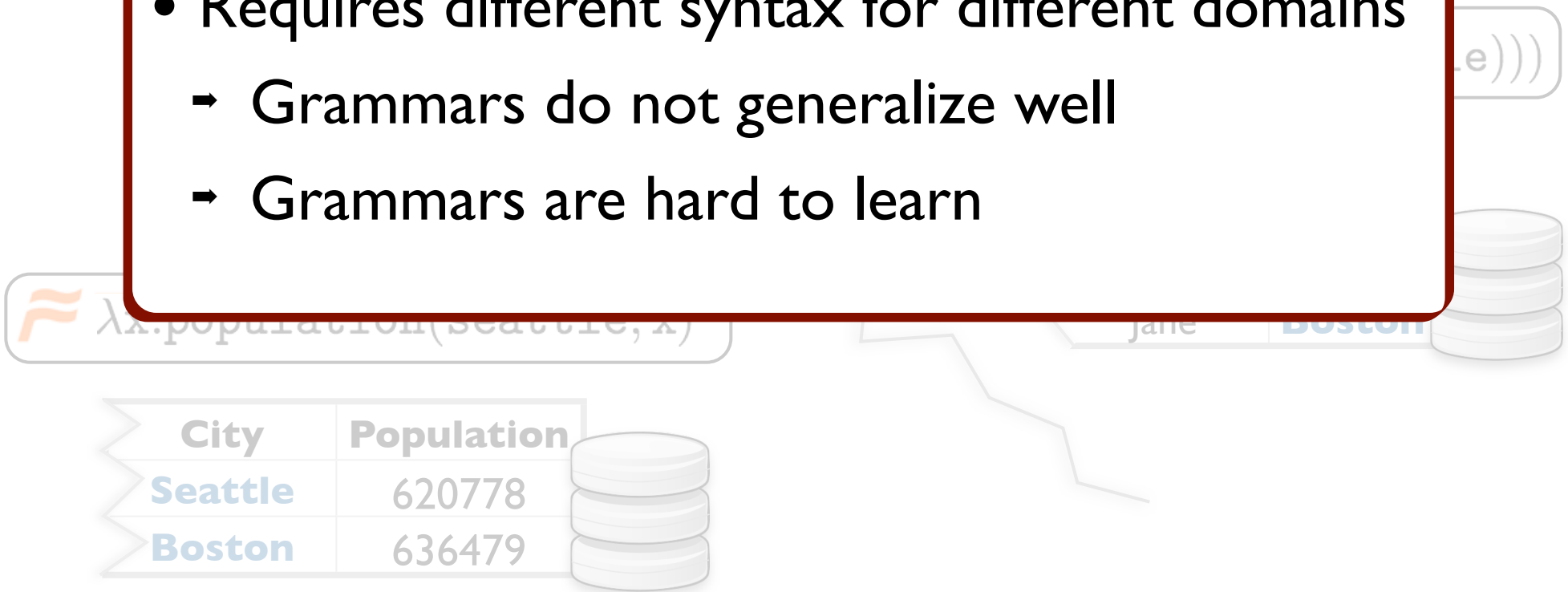
How many people live in Seattle?



Query is Domain Dependent

How many people live in Seattle?

- Requires different syntax for different domains
  - Grammars do not generalize well
  - Grammars are hard to learn



Query is Domain Dependent

How many people live in Seattle?

$\lambda x.\mathtt{population}(\mathtt{seattle}, x)$

City	Population
Seattle	450,000
Boston	750,000

How many people have won the Nobel peace prize?

$\lambda x.\mathtt{eq}(x, \mathtt{count}(\lambda y.\mathtt{person}(y) \wedge \mathtt{won}(y, \mathtt{nobel\_peace\_prize})))$

Person	Award
Nelson M.	Nobel P.P.
Mother T.	Nobel P.P.
Leymah G.	Nobel P.P.

Query is Domain Dependent

How many people live in Seattle?

$\lambda x.\mathtt{population}(\mathtt{seattle}, x)$

City	Population
Seattle	620778
Boston	636479

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2 Stage Semantic Parsing

How many people live in Seattle?

2 Stage Semantic Parsing

1. Domain independent, linguistically motivated parse.

How many people live in Seattle?

$$\lambda x.eq(x, count(\lambda y.people(y) \wedge \exists ev.live(y, ev) \wedge in(seattle, ev)))$$

2 Stage Semantic Parsing

2. Domain specific ontology match.

How many people live in Seattle?

$$\lambda x.eq(x, count(\lambda y.people(y) \wedge \exists ev.live(y, ev) \wedge in(seattle, ev)))$$

$$\lambda \mathtt{x.eq(x, count(}\lambda \mathtt{y.person(y)} \wedge \mathtt{home(y, seattle)))}$$

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Luke	Seattle
Jane	Boston

2 Stage Semantic Parsing

2. Domain specific ontology match.

How many people live in Seattle?

$\lambda x.eq(x, count(\lambda y.people(y) \wedge \exists ev.live(y, ev) \wedge in(seattle, ev)))$

$\lambda x.eq(x, count(\lambda y.person(y) \wedge home(y, seattle)))$

$\lambda x.population(seattle, x)$

City	Population
Seattle	620778
Boston	636479

Person	Home
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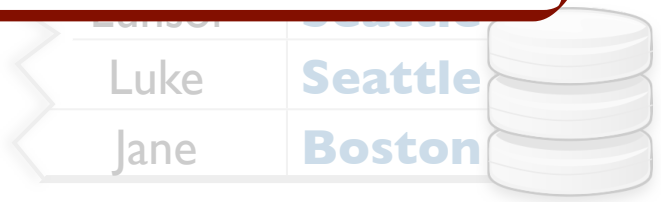
2 Stage Semantic Parsing

2. Domain specific ontology match.

How many people live in Seattle?

- All domains use same syntax that generalizes well
- Ontology match can be guided by the structure of the underspecified logical form



Overview

- 2 stage semantic parsing
  - ➡ Domain independent parsing
  - ➡ Domain dependent ontology matching
- Modeling and Inference
- Learning from Question/Answer pairs
- Experiments

2 Stage Semantic Parsing

1. Domain independent, linguistically motivated parse.
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How many people live in Seattle?

$\lambda x.eq(x, count(\lambda y.people(y) \wedge \exists ev.live(y, ev) \wedge in(seattle, ev)))$

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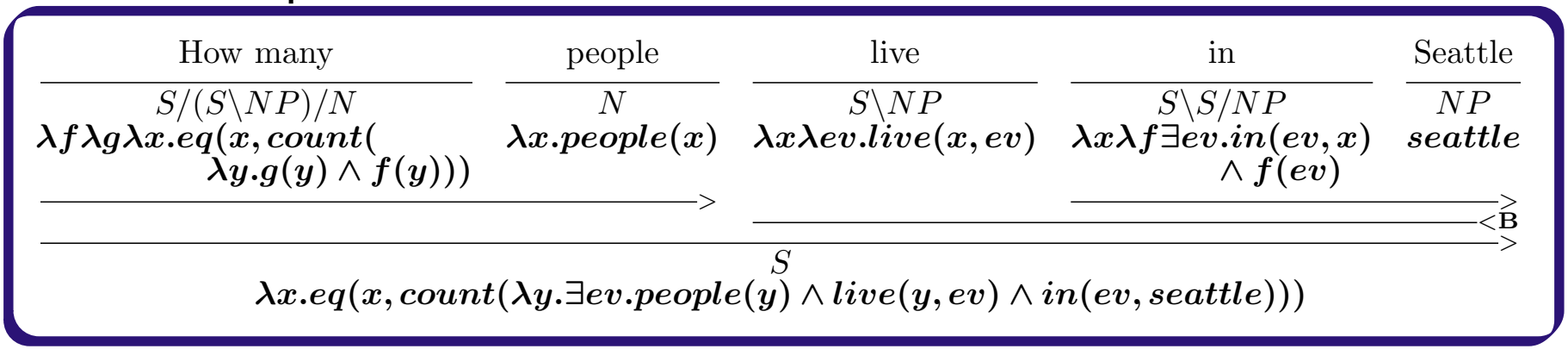
2 Stage Semantic Parsing

Domain Independent Parse

Ontology Match

2 Stage Semantic Parsing

Domain Independent Parse

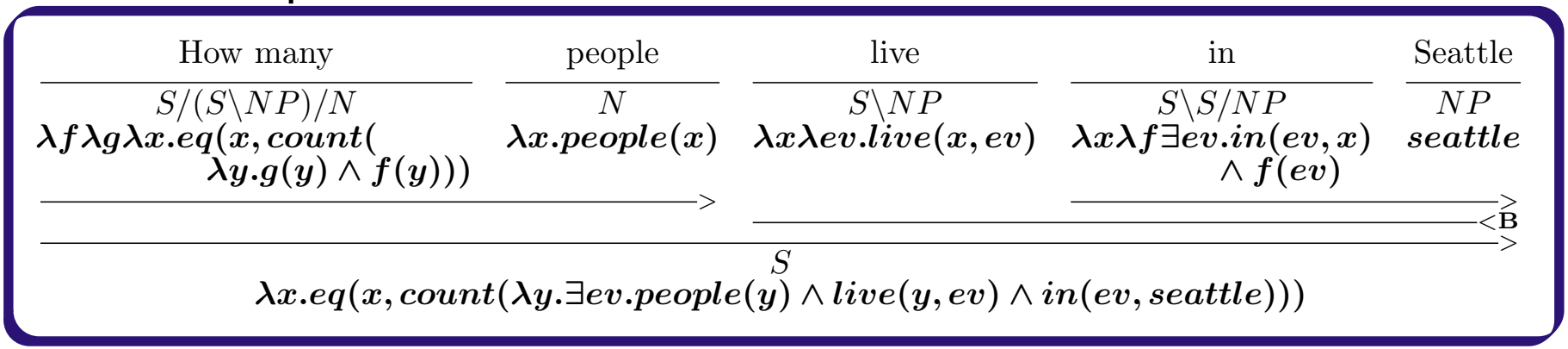


Ontology Match

Ontology Match

2 Stage Semantic Parsing

Domain Independent Parse



Ontology Match

$\lambda x.eq(x, count(\lambda y.\exists ev.people(y) \wedge live(y, ev) \wedge in(ev, seattle)))$

Structure Match

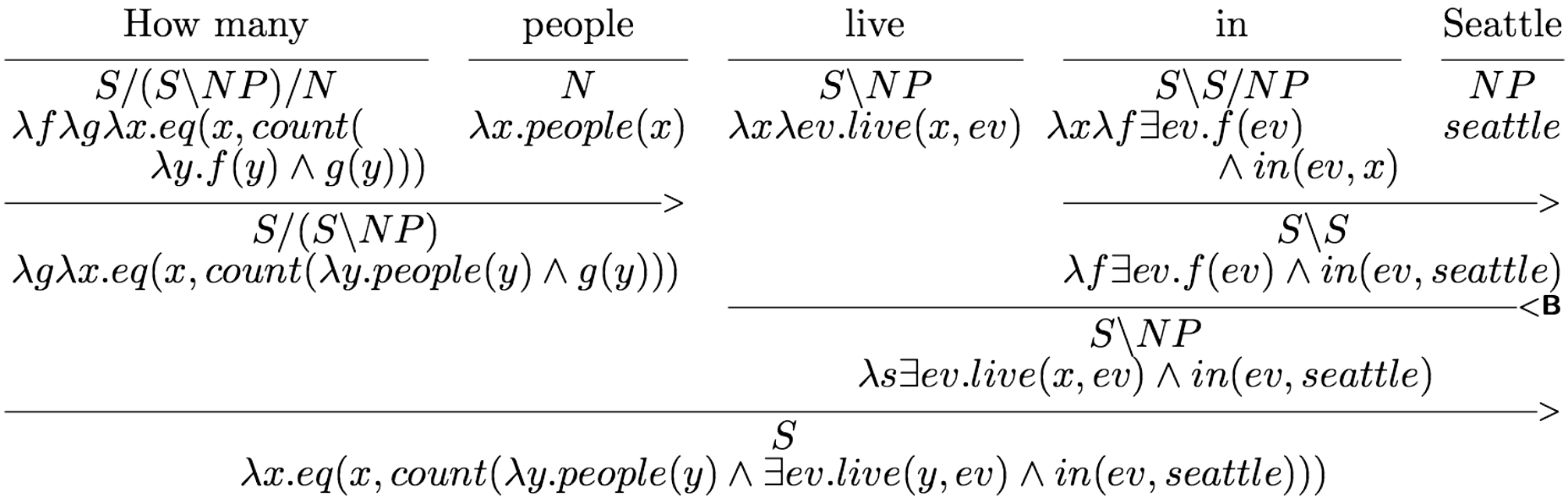
$\lambda x.how\_many\_people\_live\_in(seattle, x)$

$\lambda x.how\_many\_people\_live\_in(\texttt{seattle}, x)$

Constant Matches for ≈

$\lambda x.\texttt{population}(\texttt{seattle}, x)$

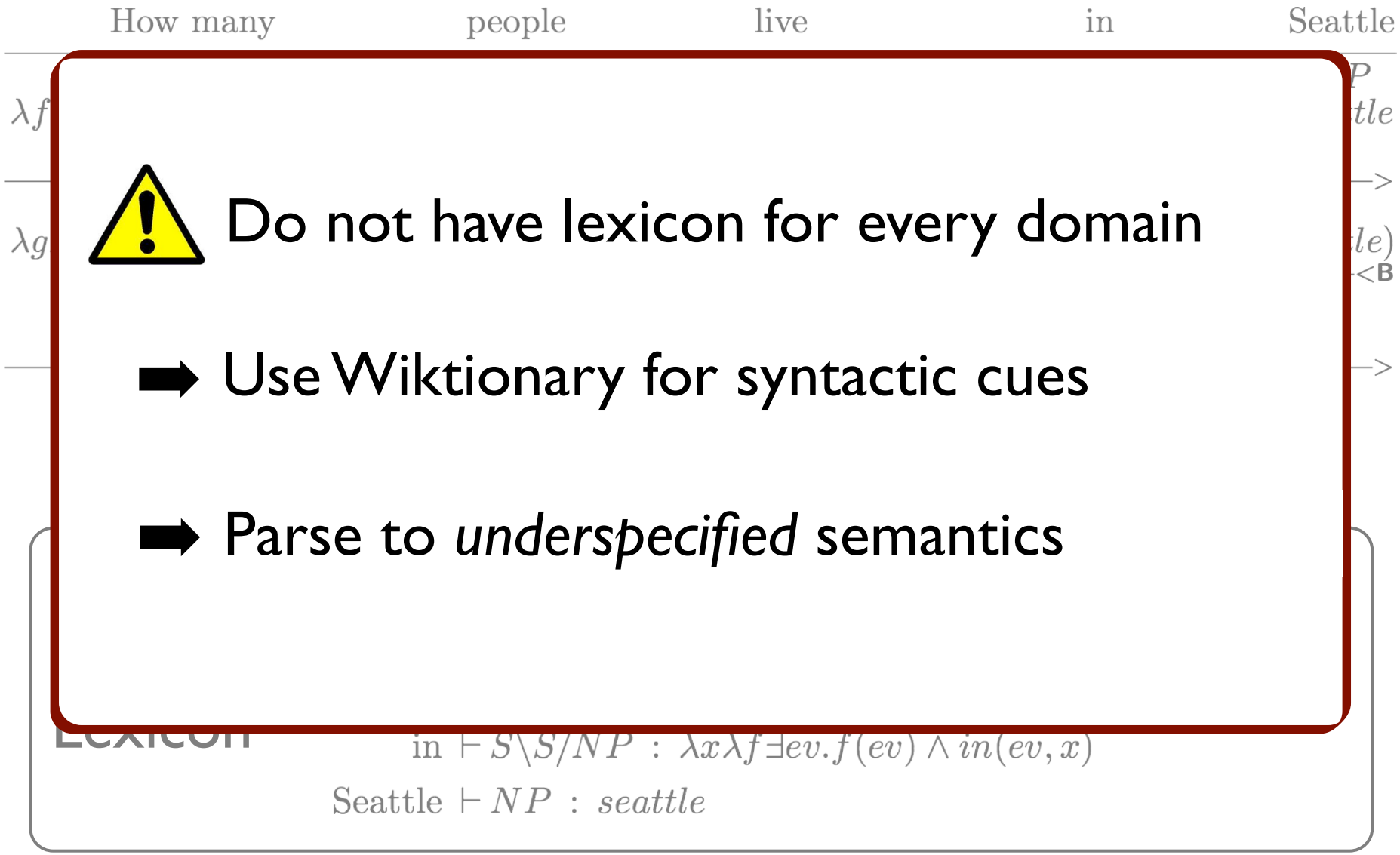
CCG Parsing



CCG Lexicon

$$\text{How many} \vdash S/(S\backslash NP)/N : \lambda f\lambda g\lambda x.eq(x, count(\lambda y.f(y) \wedge g(y)))$$
$$\text{people} \vdash N : \lambda x.people(x)$$
$$\text{live} \vdash S\backslash NP : \lambda x\lambda ev.live(x, ev)$$
$$\text{in} \vdash S\backslash S/NP : \lambda x\lambda f\exists ev.f(ev) \wedge in(ev, x)$$
$$\text{Seattle} \vdash NP : seattle$$

CCG Parsing



⚠ Do not have lexicon for every domain

➡ Use Wiktionary for syntactic cues

➡ Parse to *underspecified* semantics

Domain Independent Parsing

49 domain independent lexical items:

Word		Syntax		Underspecified semantics
How many	$\vdash$	$S/(S\backslash NP)/N$	:	$\lambda f \lambda g \lambda x.eq(x, count(\lambda y.f(y) \wedge g(y)))$
What	$\vdash$	$S/(S\backslash NP)/N$	:	$\lambda f \lambda g \lambda x.f(x) \wedge g(x)$
most	$\vdash$	NP/N	:	$\lambda f.max\_count(\lambda y.f(y))$
etc.				

Domain Independent Parsing

How many	people	live	in	Seattle
$S/(S\backslash NP)/N$ $\lambda f \lambda g \lambda x.eq(x, count($ $\lambda y.g(y) \wedge f(y)))$				

Domain Independent Parsing

How many	people	live	in	Seattle
$S/(S\backslash NP)/N$ $\lambda f \lambda g \lambda x.eq(x, count($ $\lambda y.g(y) \wedge f(y)))$				

Use Wiktionary to get part-of-speech set for words

Domain Independent Parsing

49 domain independent lexical items:

Word		Syntax		Underspecified semantics
How many	$\vdash$	$S/(S\backslash NP)/N$	:	$\lambda f \lambda g \lambda x.eq(x, count(\lambda y.f(y) \wedge g(y)))$
What	$\vdash$	$S/(S\backslash NP)/N$	:	$\lambda f \lambda g \lambda x.f(x) \wedge g(x)$
most	$\vdash$	NP/N	:	$\lambda f.max\_count(\lambda y.f(y))$
etc.				

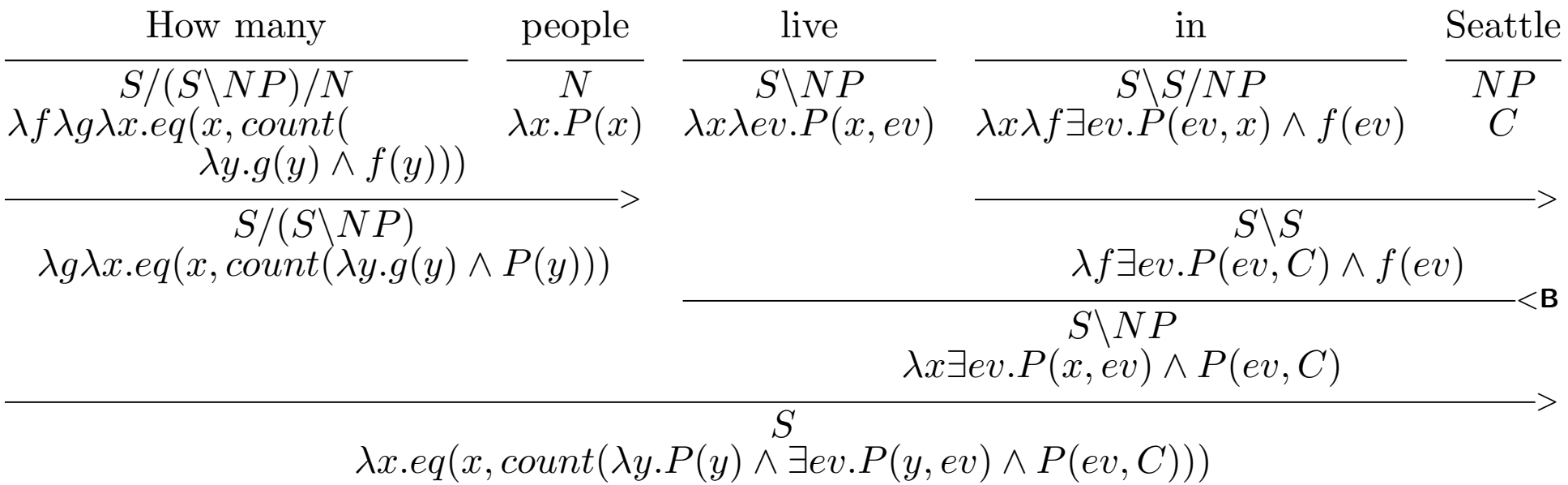
56 underspecified lexical categories:

Part-of-Speech		Syntax		Underspecified semantics
proper noun	$\vdash$	NP	:	C
noun	$\vdash$	N	:	$\lambda x.P(x)$
noun	$\vdash$	N/N	:	$\lambda f \lambda x.f(x) \wedge P(x)$
verb	$\vdash$	$S\backslash NP$	:	$\lambda \lambda ev.P(x, ev)$
verb	$\vdash$	$S\backslash NP/NP$	:	$\lambda x \lambda y \lambda ev.P(y, x, ev)$
preposition	$\vdash$	$N\backslash N/NP$	:	$\lambda f \lambda x \lambda y.P(y, x) \wedge f(y)$
preposition	$\vdash$	$S\backslash S/NP$	:	$\lambda f \lambda x \exists ev.P(ev, x) \wedge f(ev)$
etc.				

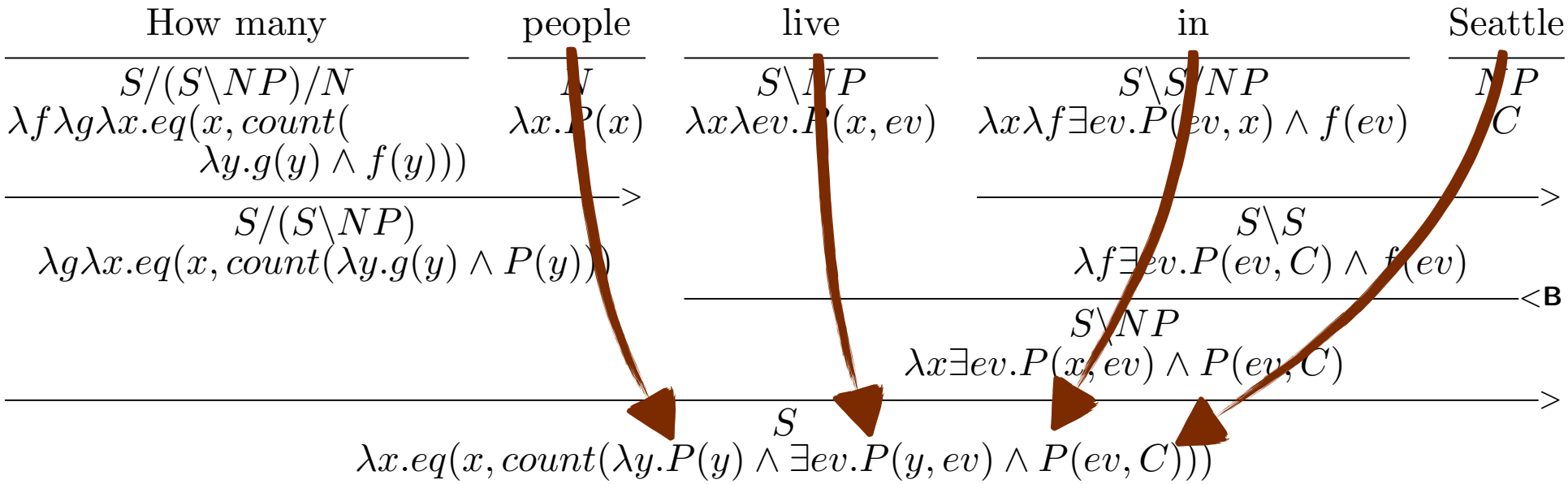
Domain Independent Parsing

How many	people	live	in	Seattle
$S/(S\backslash NP)/N$	N	$S\backslash NP$	$S\backslash S/NP$	NP
$\lambda f \lambda g \lambda x.eq(x, count(\lambda y.g(y) \wedge f(y)))$	$\lambda x.P(x)$	$\lambda x \lambda ev.P(x, ev)$	$\lambda x \lambda f \exists ev.P(ev, x) \wedge f(ev)$	C

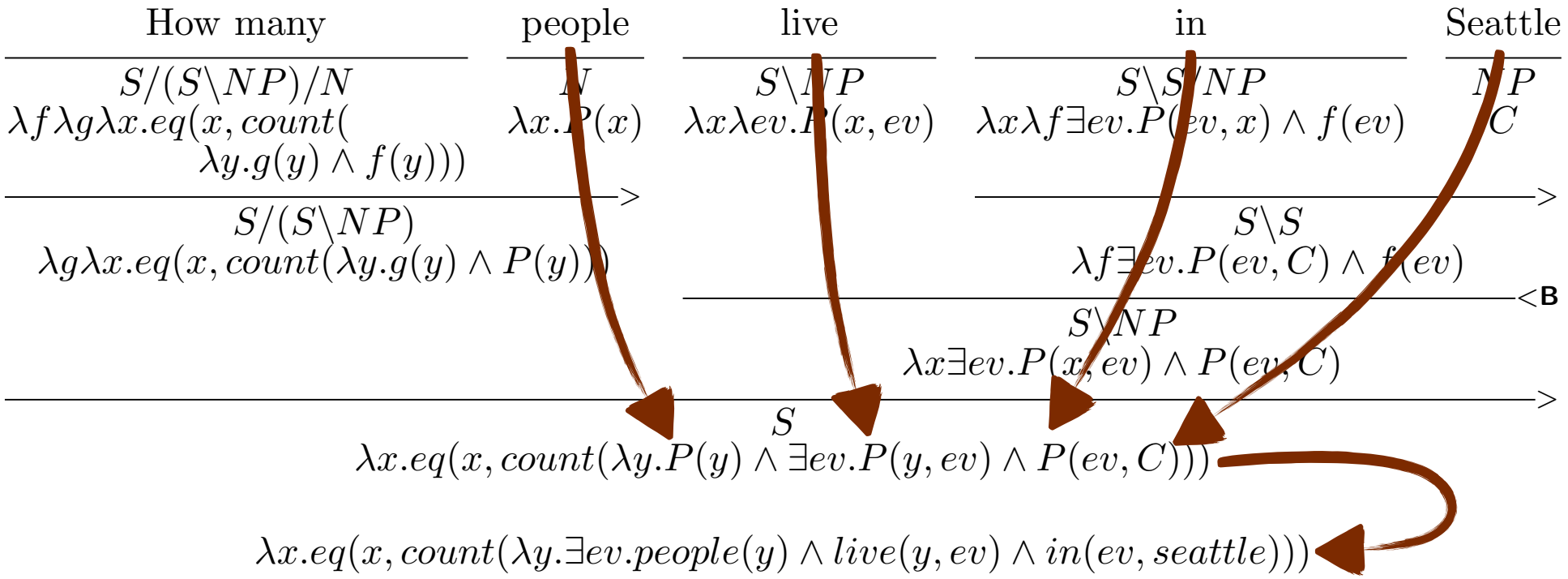
Domain Independent Parsing



Domain Independent Parsing



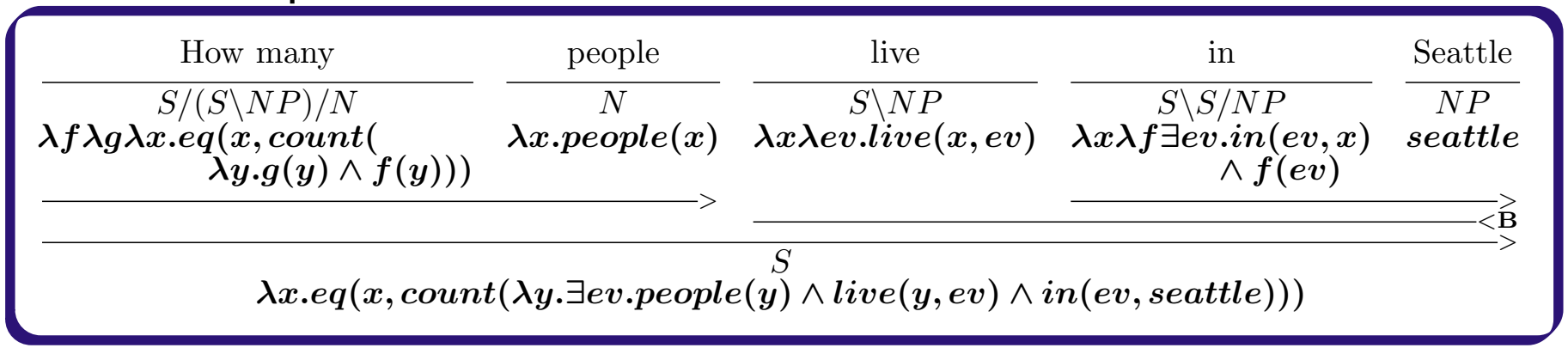
Domain Independent Parsing



String labels signify source words, not semantic constants.

2 Step Semantic Parsing

Domain Independent Parse



Ontology Match

$\lambda x.eq(x, count(\lambda y.\exists ev.people(y) \wedge live(y, ev) \wedge in(ev, seattle)))$

Structure Match

$\lambda x.how\_many\_people\_live\_in(seattle, x)$

$\lambda x.how\_many\_people\_live\_in(\texttt{seattle}, x)$

Constant Matches for ≈

$\lambda x.\texttt{population}(\texttt{seattle}, x)$

Structural Match

Collapse and expand subexpressions in underspecified logical form with operators that:

1. Collapse simple typed sub-expression
2. Collapse complex typed sub-expression
3. Expand predicate

New example

How many people ride the monorail in Seattle daily?

$\lambda x.eq(x, count(\lambda y.people(y) \wedge \exists e.ride(y, \iota z.monorail(z) \wedge in(z, seattle), e) \wedge daily(e)))$

λx.transit_system/daily_riders(seattle_monorail, x)

Structural Match

1. Find subexpression with type allowed in KB

$$\lambda x.eq(x, count(\lambda y.people(y) \wedge \exists e.ride(y, \iota z.monorail(z) \wedge in(z, seattle), e) \wedge daily(e)))$$

2. Replace with new underspecified constant

Structural Match

1. Find subexpression with type allowed in KB

$$\lambda x.eq(x, count(\lambda y.people(y) \wedge \exists e.ride(y, \iota z.monorail(z) \wedge in(z, seattle)), e) \wedge daily(e)))$$

entity typed subexpression

2. Replace with new underspecified constant

$$\lambda x.eq(x, count(\lambda y.people(y) \wedge \exists e.ride(y, monorail\_in\_seattle), e) \wedge daily(e)))$$

Structural Match

1. Find subexpression with type allowed in KB

$$\lambda x.eq(x, count(\lambda y.people(y) \wedge \exists e.ride(y, \iota z.monorail(z) \wedge in(z, seattle), e) \wedge daily(e)))$$

integer typed subexpression

2. Replace with new underspecified constant

$$\lambda x.eq(x, count(\lambda y.people(y) \wedge \exists e.ride(y, monorail\_in\_seattle), e) \wedge daily(e)))$$

$$\lambda x.eq(x, how\_many\_people\_ride\_daily\_the\_monorail\_in\_seattle)$$

Structural Match

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$$\lambda x.eq(x, count(\lambda y.people(y) \wedge \exists e.ride(y, \iota z.monorail(z) \wedge in(z, seattle), e) \wedge daily(e)))$$

integer typed subexpression

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$$\lambda x.eq(x, count(\lambda y.people(y) \wedge \exists e.ride(y, monorail\_in\_seattle), e) \wedge daily(e)))$$

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<e,<e,t>> typed subexpression

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$$\lambda x.eq(x, count(\lambda y.people(y) \wedge ride\_daily(y, monorail\_in\_seattle)))$$

Structural Match

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2. Replace with new underspecified constant

$$\lambda x.eq(x, count(\lambda y.people(y) \wedge ride\_daily(y, monorail\_in\_seattle)))$$

$$\lambda x.how\_many\_people\_ride\_daily(the\_monorail\_in\_seattle, x)$$

Structural Match

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Structural Match

$$\lambda x.how\_many\_people\_ride\_daily(the\_monorail\_in\_seattle, x)$$

Constant Match

Replace constants with constants from KB

$$\lambda x.how\_many\_people\_ride\_daily(the\_monorail\_in\_seattle, x)$$

Assume constants have English string labels!

Constant Match

Replace constants with constants from KB

$$\lambda x.how\_many\_people\_ride\_daily(the\_monorail\_in\_seattle, x)$$

λx.transit_system/daily_riders(seattle_monorail, x)

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$\lambda x.how\_many\_people\_ride\_daily(\texttt{seattle\_monorail},\ x)$

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Constant Match

Replace constants with constants from KB

$\lambda x.how\_many\_people\_ride\_daily(the\_monorail\_in\_seattle.\, x)$

$\lambda x.how\_many\_people\_ride\_daily(\texttt{seattle\_monorail}, x)$

$\lambda x.\texttt{transit\_system/daily\_riders}(\texttt{seattle\_monorail}, x)$

$\approx \lambda x.\texttt{transit\_system/daily\_riders}(\texttt{seattle\_monorail}, x)$

Overview

- 2 stage semantic parsing
  - ➡ Domain independent parsing
  - ➡ Domain dependent ontology matching
- Modeling and Inference
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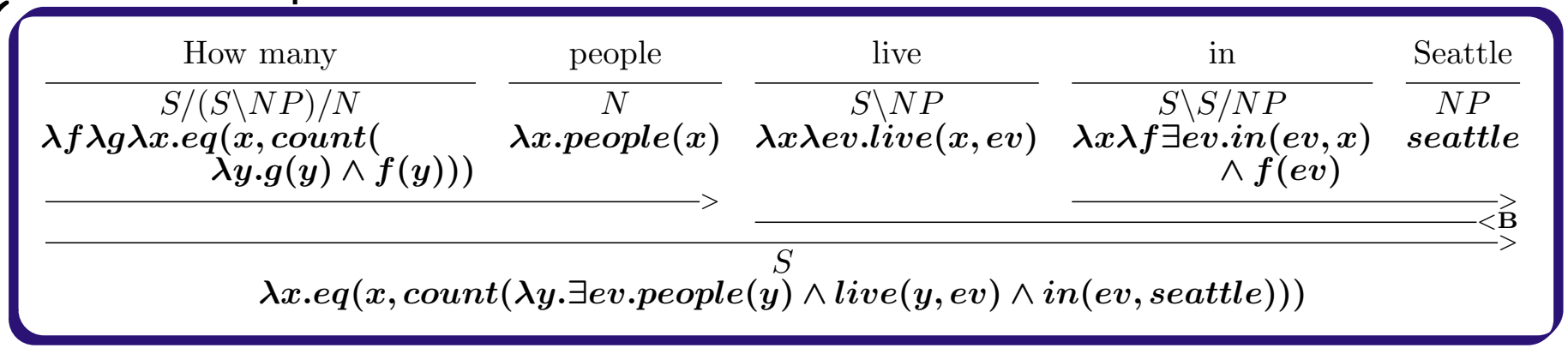
2 Stage Semantic Parsing

Domain Independent Parse



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$\lambda x.\texttt{population}(\texttt{seattle}, x)$

Scoring Derivations

Derivations d are scored using a linear model:

$$\text{score}(d) = \phi(d)\theta$$

with feature vector $\phi(d)$ that decomposes over:

- Domain independent parse
- Structural match
- Constant match
  - **Lexical features**
  - **Knowledge base features**

Lexical Features

When did Prairie Home Companion first air?

$\lambda x.when\_first\_air(prarie\_home\_companion, x)$

How high is Niagara Falls?

$\lambda x.high(niagara\_falls, x)$

- Exact string match
- Stemmed string match
- Synonym match
- Wiktionary gloss overlap

Lexical Features

elevation (*plural* **elevations**)

1. The act of raising from a lower place, condition, or quality to a higher; said of material things, persons, the mind, the voice, etc.; as, the elevation of grain; elevation to a throne; elevation to sainthood; elevation of mind, thoughts, or character.
2. The condition of being or feeling elevated; heightened; exaltation.

high (*comparative* **higher**, *superlative* **highest**)

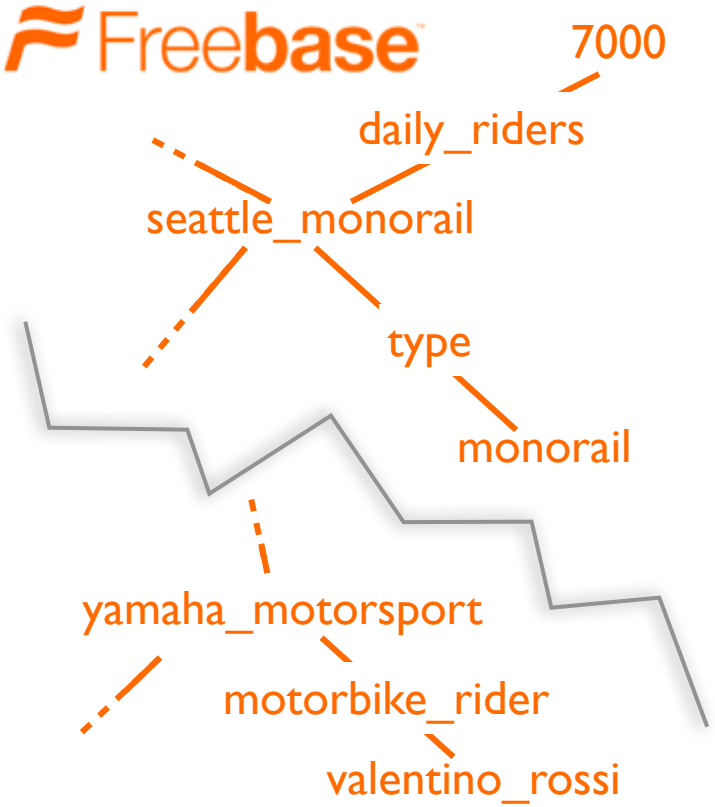
1. Being elevated in position or status, a state of being above many things. [quotations ▼]

$$\lambda x.high(niagara\_falls, x)$$

$$\approx \lambda \mathtt{x.location.geocode.elevation(niagara\_falls, x)}$$

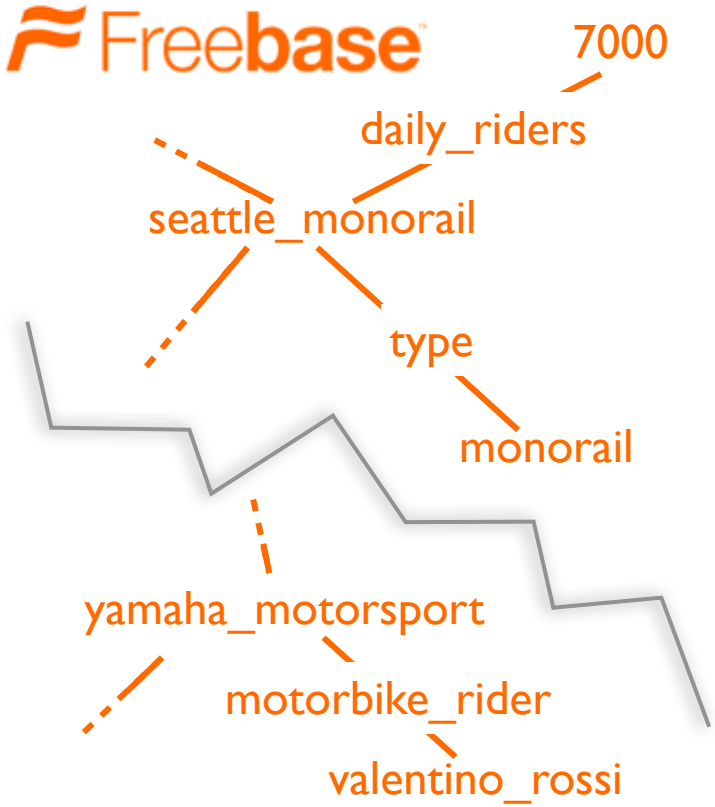
- Exact string match.
- Stemmed string match.
- Synonym match.
- Wiktionary gloss overlap.

Knowledge Base Features

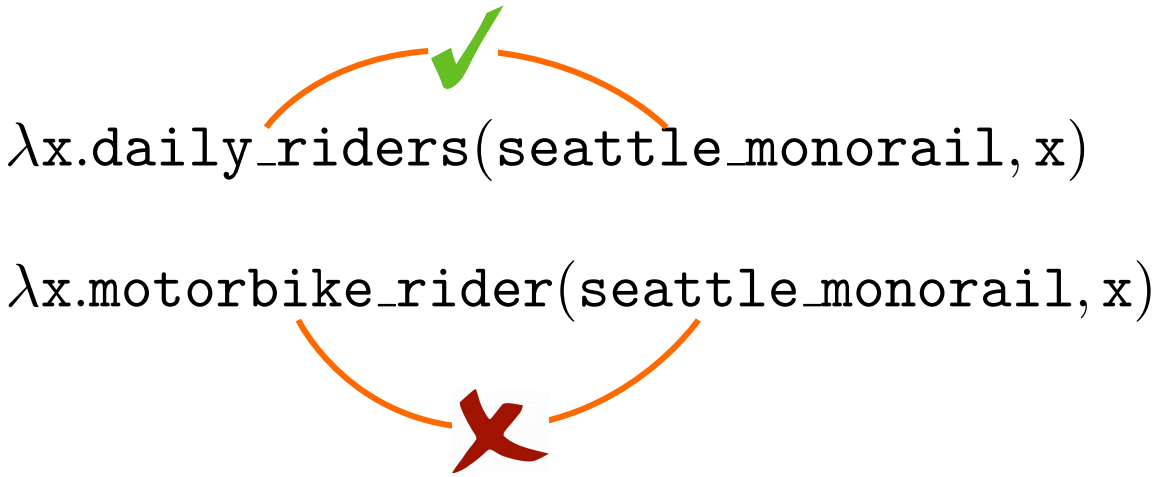


Test logical structure to see if it can exist in knowledge base.

Knowledge Base Features

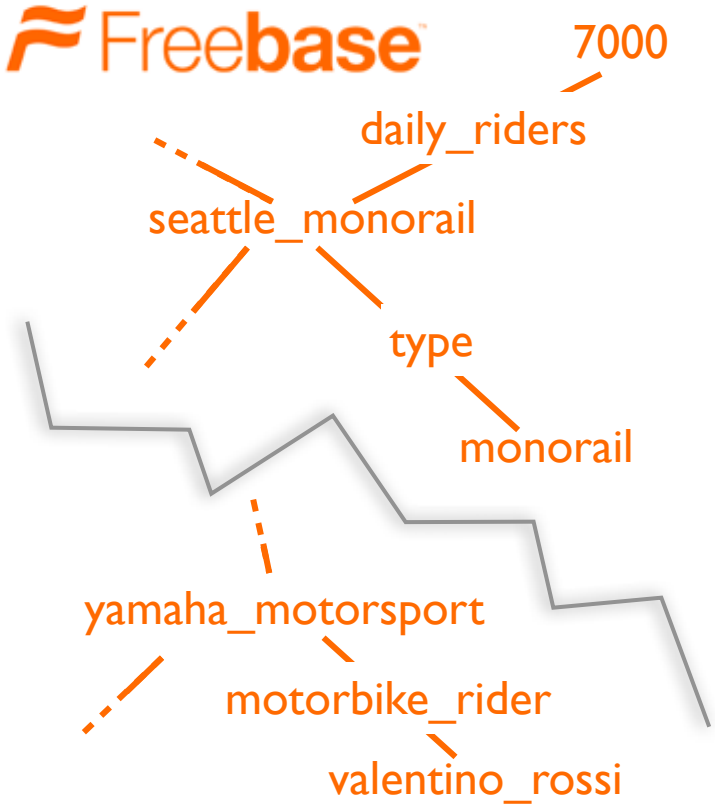


Predicted Logical Form



Test logical structure to see if it can exist in knowledge base.

Knowledge Base Features



Predicted Logical Form

$\lambda x \lambda y.\texttt{motorbike\_rider}(x, y) \wedge \texttt{monorail}(x)$

$\lambda x \lambda y.\texttt{daily\_riders}(x, y) \wedge \texttt{monorail}(x)$

Test logical structure to see if it can exist in knowledge base.

Inference

Ontology matching step is:

- Exponential in arity of most complex predicate
- Polynomial in number of logical symbols
- Linear in the size of the knowledge base

➡ Use dynamic programming

➡ Prune heavily according to local score

➡ Call constant matching operators greedily

2 Stage Semantic Parsing

Domain Independent Parse

Ontology Match

d

$$\lambda x.eq(x, count(\lambda y.\exists ev.people(y) \wedge live(y, ev) \wedge in(ev, seattle)))$$

$$\lambda x.eq(x, count(\lambda y.\exists ev.people(y) \wedge live(y, ev) \wedge in(ev, \texttt{seattle})))$$

$$\lambda x.how\_many\_people\_live\_in(\texttt{seattle}, x)$$

$$\lambda x.\texttt{population}(\texttt{seattle}, x)$$

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Learning

Input

Q/A pairs $\{(x_i, a_i) : i = 1, \ldots, n\}$

Knowledge Base, Wiktionary, Underspecified Lexicon

Algorithm

For $i = 1, \ldots, n$:

$C \leftarrow$ Max scoring correct parses of x_i

$W \leftarrow$ Margin violating incorrect parses of x_i

$$\theta = \theta + \frac{1}{|C|} \sum_{c \in C} \phi(c) - \frac{1}{|W|} \sum_{w \in W} \phi(w)$$

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  - ➡ Domain dependent ontology matching
- Modeling and Inference
- Learning from Question/Answer pairs
- Experiments

Experiments

Q/A from databases - evaluate on exact answer match

Freebase917

- 642 training sentences, 275 test sentences
- 135 million facts, 18 million entities, 2000 relations

GeoQuery

- 600 training sentences, 280 test sentence
- 14018 facts, 3839 entities, 12 relations
- High degree of compositional complexity

Feature initialization:

Lexical - Prefer exact and partial string match

Knowledge base - Prefer concepts in knowledge base

Related Work

Learning From Q/A Pairs:

- Clarke et.al. 2010
- Goldwasser et.al. 2011
- Liang et.al. 2011 (DCS)
- Berant et.al. 2013

Learning CCG from Labelled Logical Forms:

- Kwiatkowski et.al. 2011 (FUBL)
- Cai & Yates 2013

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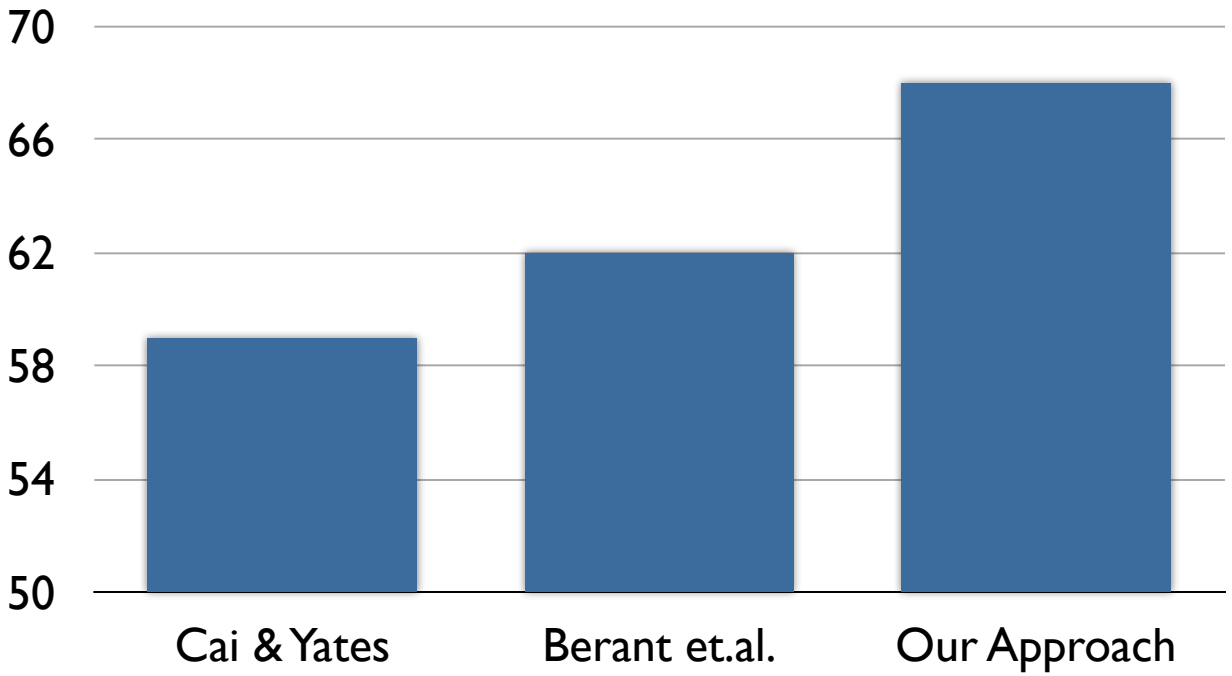
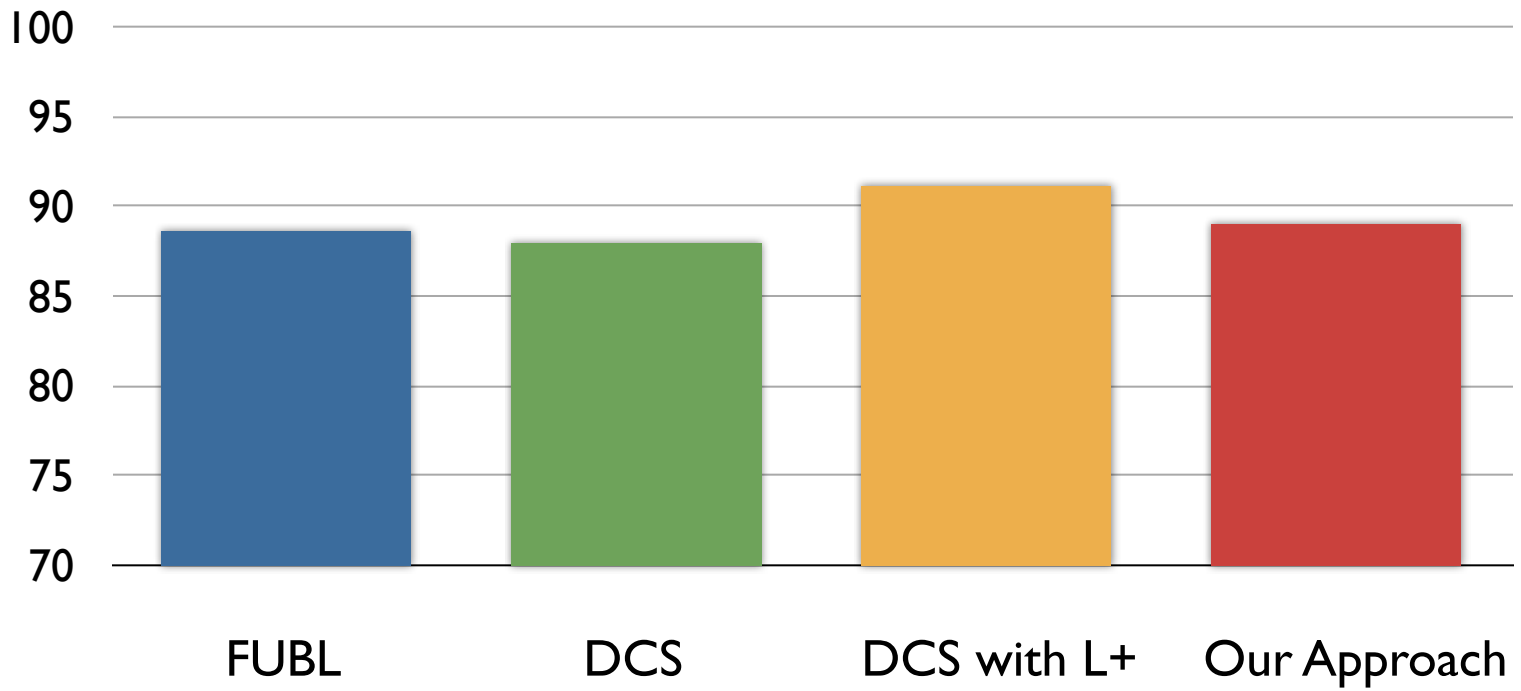
Experiments

Freebase 917



Experiments

GeoQuery



Example Parses

How many operating systems is Adobe Flash compatible with?

$$\lambda \mathtt{x}.\mathtt{eq}(\mathtt{x}, \mathtt{count}(\lambda \mathtt{y}.\mathtt{software\_compatibility}\ .\mathtt{operating\_system}(\mathtt{adobe\_flash}, \mathtt{y})))$$

Example Parses

Who is the CEO of Save-A-Lot?

$$\lambda x.\texttt{person}(x) \wedge \exists y.\texttt{organization}(y, \texttt{savealot}) \wedge$$
$$\approx \quad \texttt{board\_member.leader\_of}(x, y) \wedge \texttt{leadership.role}(y, \texttt{ceo})$$

Example Errors

How many children does Jerry Seinfeld have?

Target:


$\lambda x.\mathtt{eq}(x, \mathtt{count}(\lambda y.\mathtt{person.children}(\mathtt{jerry\_seinfeld}, y)))$

Prediction:


$\lambda x.\mathtt{eq}(x, \mathtt{count}(\lambda y.\mathtt{person.children}(y, \mathtt{jerry\_seinfeld})))$

Example Errors

What programming languages were used for AOL instant messenger?

Target:

$\approx$ $\lambda x.\texttt{languages\_used}(\texttt{aol\_instant\_messenger}, x)$

Prediction:

$\approx$ $\lambda x.\texttt{languages\_used}(\texttt{aol\_instant\_messenger}, x) \wedge \texttt{programming\_language}(x)$

Future Work

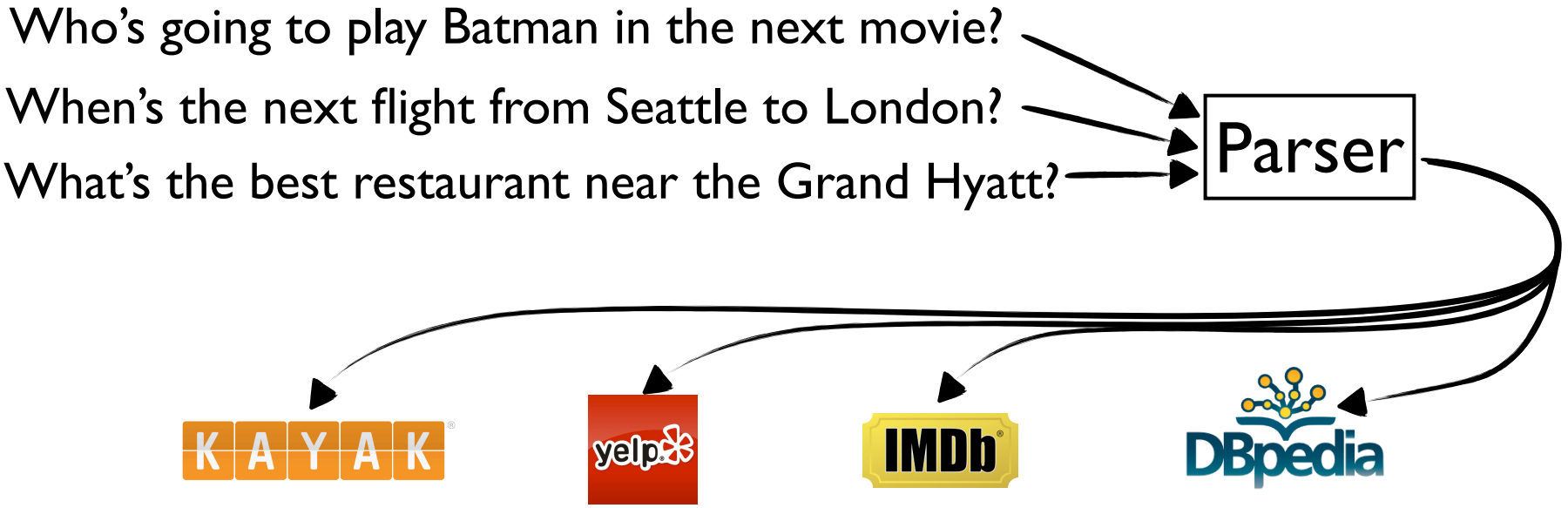
Information Extraction:

Alan Turing was a British mathematician, logician, cryptanalyst, and computer scientist.

$$\texttt{nationality}(\texttt{AT}, \texttt{UK}) \wedge \texttt{notable\_for}(\texttt{AT}, \texttt{mathematian}) \wedge \texttt{profession}(\texttt{AT}, \texttt{logic})) \wedge \texttt{research}(\texttt{AT}, \texttt{cryptanalysm}) \wedge \texttt{notable\_type}(\texttt{AT}, \texttt{compsci})$$

Freebase

Multiple databases:



Questions

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