Towards a Compositional Typed Semantics for Universal Dependencies

Siva Reddy

School of Informatics
The University of Edinburgh

People

Mirella Lapata

Mark Steedman

People

Mirella Lapata

Mark Steedman

Oscar Täckström

Dipanjan Das

Tom Kwiatkowski

Michael Collins

Slav Petrov

Syntax helps Semantics

kotini	aratipandu	tinindi
monkey	*banana*	*eat*

Syntax helps Semantics

kotini	aratipandu	tinindi
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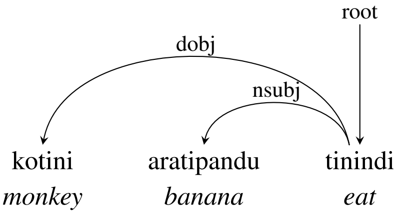
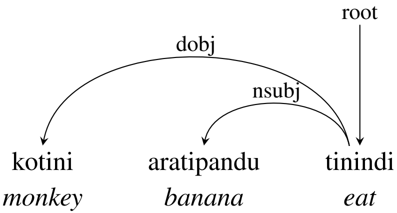
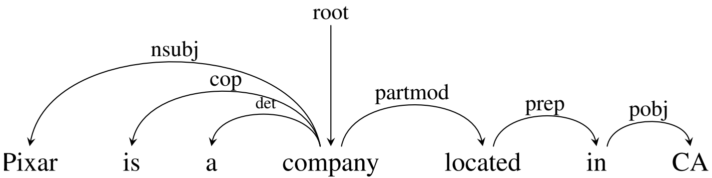
Syntax helps Semantics



Syntax helps Semantics

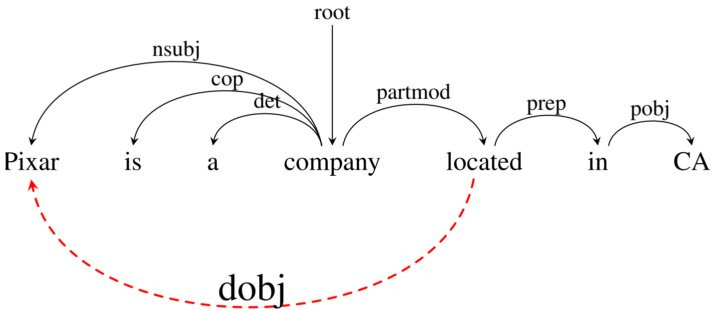


Dependencies to Logical Forms



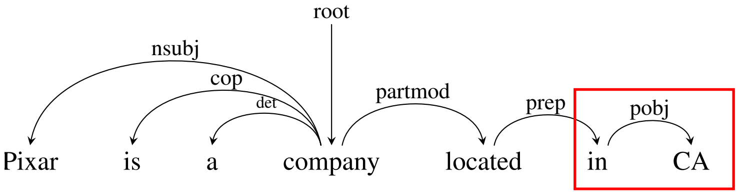
$$\exists z.\text{company}(\text{Pixar}) \wedge \text{located}(z_e) \wedge \text{arg}_2(z_e, \text{Pixar}) \wedge \text{arg}_{\text{in}}(z_e, \text{CA})$$

Dependencies to Logical Forms



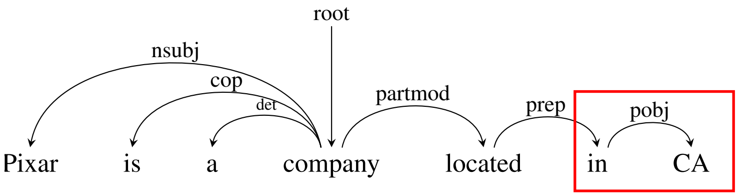
$$\exists z.\text{company}(\text{Pixar}) \wedge \textcolor{red}{\text{located}(z_e) \wedge \text{arg}_2(z_e, \text{Pixar})} \wedge \text{arg}_{\text{in}}(z_e, \text{CA})$$

Dependencies to Logical Forms



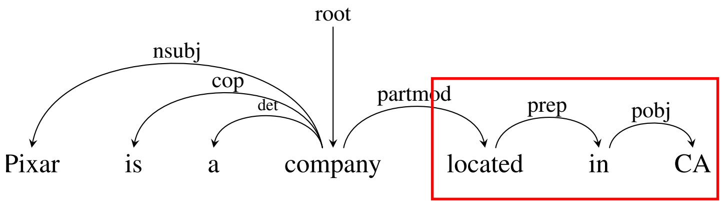
$$(pobj \quad \text{in} \quad \text{CA})$$

Dependencies to Logical Forms



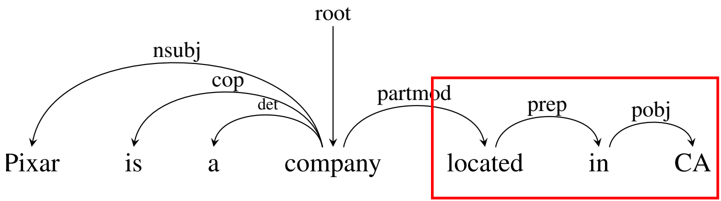
$$\frac{\begin{array}{ccc} (\mathit{pobj} & \text{in} & \text{CA}) \\ \lambda f g z . \exists x . & \lambda x . \text{empty}(x) & \lambda x . \text{CA}(x_a) \\ f(z) \wedge g(x) & & \\ \text{arg}_{\text{in}}(z_e, x_a) & & \end{array}}{\lambda z .\ \text{arg}_{\text{in}}(z_e, x_a) \wedge \text{CA}(x_a)}$$

Dependencies to Logical Forms



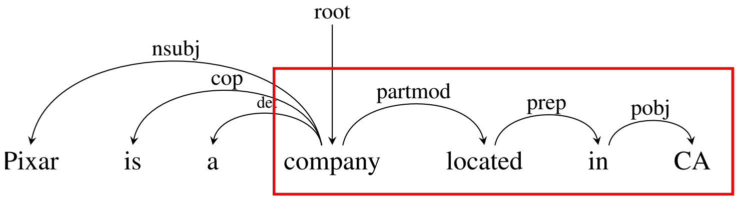
$(prep \quad \text{located} \quad \text{in CA})$

Dependencies to Logical Forms



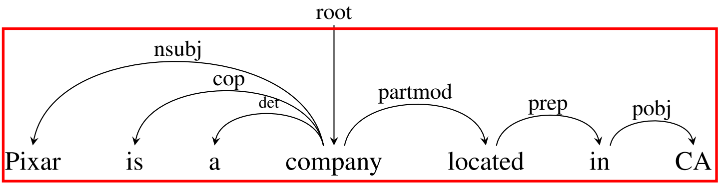
$$\dfrac{\begin{array}{ccc} (\textit{prep} & \text{located} & \text{in CA}) \\ \lambda f g z.\exists x. & \lambda x.\text{located}(x_e) & \overline{\phantom{\lambda z. \arg_{\text{in}}(z_e, x_a) \wedge \text{CA}(x_a)}} \\ f(z) \wedge g(x) \wedge & & \lambda z.\ \text{arg}_{\text{in}}(z_e, x_a) \wedge \text{CA}(x_a) \end{array}}{\lambda z.\text{located}(z_e) \wedge \text{CA}(x_a) \wedge \text{arg}_{\text{in}}(z_e, x_a))}$$

Dependencies to Logical Forms



$$
\dfrac{
\begin{array}{ccc}
\begin{array}{c}(\mathit{partmod} \\ \lambda f g x.\exists z. \\ f(x) \wedge g(x) \wedge \\ \mathrm{arg}_2(z_e, x_a)\end{array}
&
\begin{array}{c}\text{company} \\ \lambda x.\mathrm{compay}(x_e)\end{array}
&
\dfrac{\text{located in CA})}{\lambda g z.\exists x.\mathrm{located}(z_e) \wedge \mathrm{CA}(x_a) \wedge \mathrm{arg}_{\mathrm{in}}(z_e, x_a)}
\end{array}
}{
\lambda x.\exists y z.\mathrm{company}(x_a) \wedge \mathrm{located}(z_e) \wedge \mathrm{CA}(y_a) \wedge \mathrm{arg}_2(z_e, x_a) \wedge \mathrm{arg}_{\mathrm{in}}(z_e, y_a)
}
$$

Dependencies to Logical Forms



$$\exists z.\mathrm{company}(\mathrm{Pixar}) \wedge \mathrm{located}(z_e) \wedge \mathrm{arg}_2(z_e, \mathrm{Pixar}) \wedge \mathrm{arg}_{\mathrm{in}}(z_e, \mathrm{CA})$$

Why Logical Forms?

Logical froms are useful!

- Semantic Parsing [Zelle & Mooney, 1996; Zettlemoyer & Collins, 2005]
- Simplification [Narayan & Gardent, 2014]
- Paraphrasing [Pavlick et al., 2015]
- Information Extraction [Rocktäschel et al., 2015]
- Summarization [Liu et al., 2015]

Where do logical forms come from?

From rich linguistic formalisms

- CCG [Bos et al., 2004; Lewis & Steedman, 2013]
- HPSG [Copestake et al., 2001]
- LFG [Dalrymple et al., 1995]
- TAG [Joshi et al., 1995]

CCG has been a popular choice

- Tight integration between syntax and semantics
- No treebanks for many languages

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Why from dependencies?

Treebanks in more than 40 languages.

(e.g., Universal Dependencies [Nivre et al., 2016])

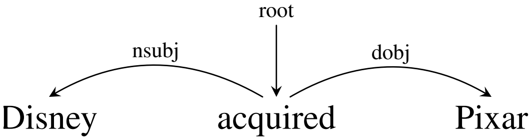
Very accurate parsers.

[Andor et al., 2016; Chen & Manning, 2014]

This Work

- Dependency structures to logical forms using lambda calculus
- We use these logical forms for Freebase Semantic Parsing
- State-of-the-art on Free917, and competitive results on WebQuestions QA datasets

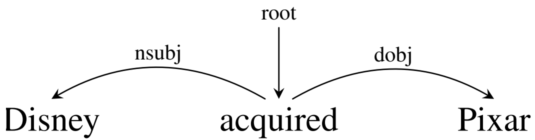
Dependencies to Logical Forms



$$\lambda z.\exists xy.\text{acquired}(z_e) \wedge \text{Pixar}(y_a) \wedge \text{Disney}(x_a) \wedge$$
$$\text{arg}_1(z_e, x_a) \wedge \text{arg}_2(z_e, y_a)$$

Dependencies to Logical Forms

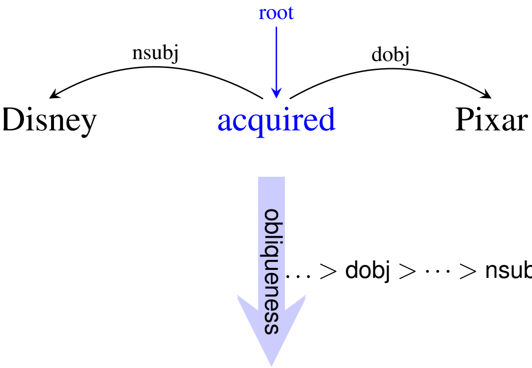
Our Approach



Let dependency labels drive the composition

Dependencies to Logical Forms

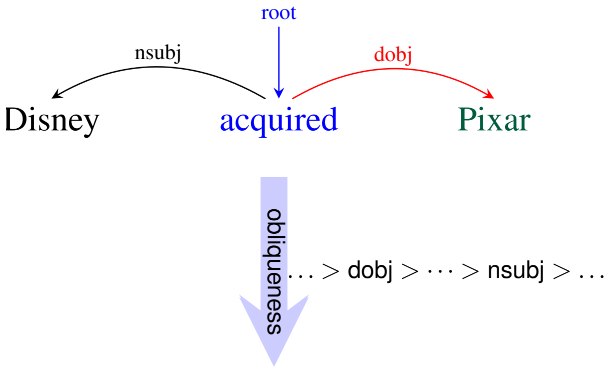
Our Approach



$\ldots >$ dobj $> \cdots >$ nsubj $> \ldots$

Dependencies to Logical Forms

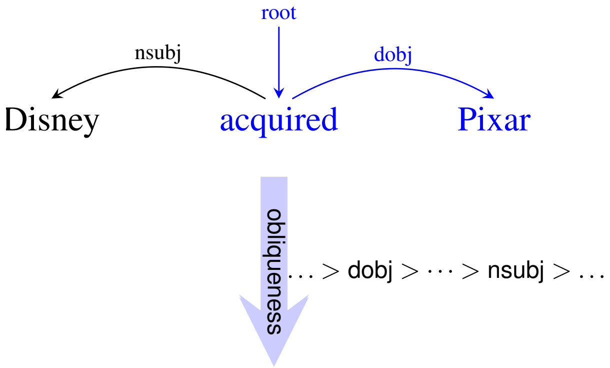
Our Approach



(dobj acquired Pixar)

Dependencies to Logical Forms

Our Approach



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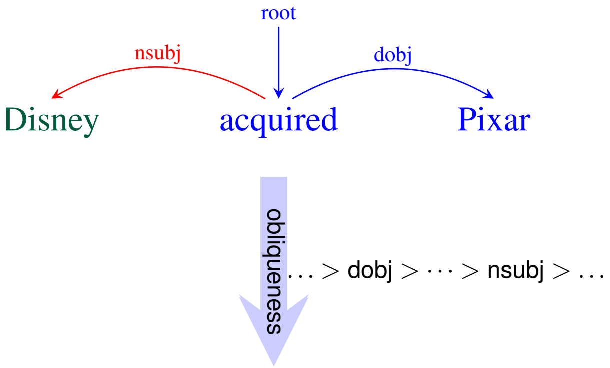
Dependencies to Logical Forms

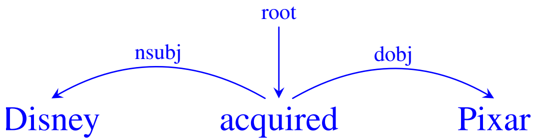
Our Approach

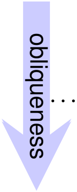


(nsubj (dobj acquired Pixar) Disney)

Dependencies to Logical Forms

Our Approach



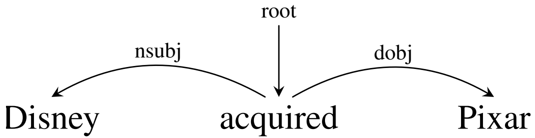


$\ldots > \text{dobj} > \cdots > \text{nsubj} > \ldots$

(nsubj (dobj acquired Pixar) Disney)

Dependencies to Logical Forms

Our Approach

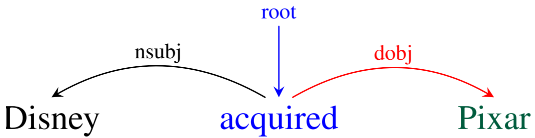


(nsubj (dobj acquired Pixar) Disney)

$$\lambda z.\exists xy.\mathrm{acquired}(z_e) \wedge \mathrm{Pixar}(y_a) \wedge \mathrm{Disney}(x_a) \wedge \\ \mathrm{arg}_1(z_e, x_a) \wedge \mathrm{arg}_2(z_e, y_a)$$

Dependencies to Logical Forms

Lambda Calculus

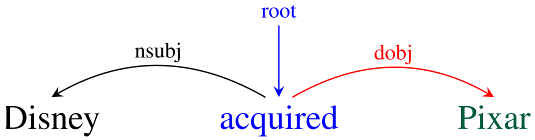


Lambda Calculus Basic Types

- Individuals: $\mathbf{Ind}$ (also denoted by $\cdot_a$)
- Events: $\mathbf{Event}$ (also denoted by $\cdot_e$)
- Truth values: $\mathbf{Bool}$

Dependencies to Logical Forms

Lambda Calculus



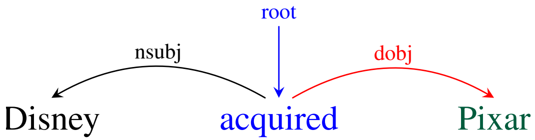
Lambda Expression for words

$$\text{acquired} \Rightarrow \lambda x.\, \text{acquired}(x_e)$$

$$\text{Pixar} \Rightarrow \lambda x.\, \text{Pixar}(x_a)$$

Dependencies to Logical Forms

Lambda Calculus

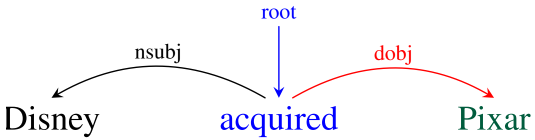


Lambda Expression for dependency labels

$$\text{dobj} \Rightarrow \lambda \mathbf{f}\ \mathbf{g}\ \mathbf{z}\ .\ \exists \mathbf{x}\ .\ \mathbf{f}(\mathbf{z}) \wedge \mathbf{g}(\mathbf{x}) \wedge \mathbf{arg_2}(\mathbf{z_e}, \mathbf{x_a})$$

Dependencies to Logical Forms

Lambda Calculus



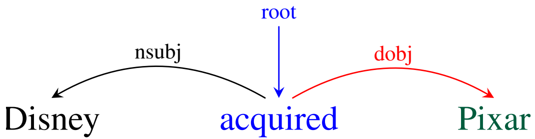
Lambda Expression for dependency labels

dobj $\Rightarrow \lambda \mathbf{f}\ \mathbf{g}\ \mathbf{z}\ .\ \exists \mathbf{x}\ .\ \mathbf{f}(\mathbf{z}) \quad \wedge \quad \mathbf{g}(\mathbf{x}) \quad \wedge \quad \mathbf{arg_2}(\mathbf{z_e}, \mathbf{x_a})$

This operation mirrors the tree structure

Dependencies to Logical Forms

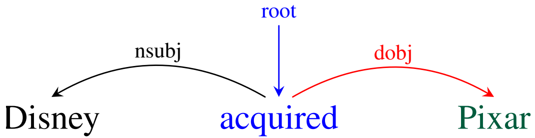
Composition



(**dobj**	**acquired**	**Pixar**)
$\lambda f g z . \exists y . f(z) \wedge g(y) \wedge \mathrm{arg}_2(z_e, y_a)$	$\lambda z . \mathrm{acquired}(z_e)$	$\lambda y . \mathrm{Pixar}(y_a)$

Dependencies to Logical Forms

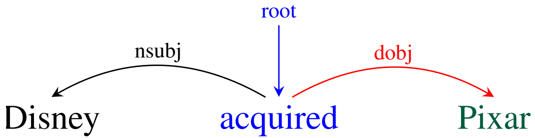
Composition



$$\dfrac{(\textbf{dobj} \quad \textbf{acquired} \quad \textbf{Pixar}) \qquad \begin{array}{c}\lambda f g z.\exists y. \\ f(z) \land g(y) \land \\ \text{arg}_2(z_e, y_a)\end{array} \quad \lambda z.\text{acquired}(z_e) \quad \lambda y.\text{Pixar}(y_a)}{\begin{array}{c}\lambda g z.\ \exists y.\ \text{acquired}(z_e) \land g(y) \\ \land\ \text{arg}_2(z_e, y_a)\end{array}}$$

Dependencies to Logical Forms

Composition



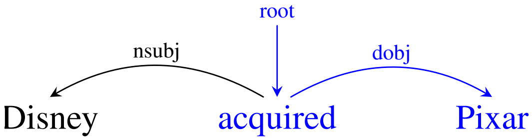
$$\begin{array}{ccc}
(\textbf{dobj} & \textbf{acquired} & \textbf{Pixar}) \\
\lambda f g z.\exists y. & \lambda z.\text{acquired}(z_e) & \lambda y.\text{Pixar}(y_a) \\
f(z) \wedge g(y) \wedge & & \\
\text{arg}_2(z_e, y_a) & &
\end{array}$$

$$\frac{}{\lambda g z.\ \exists y.\ \text{acquired}(z_e) \wedge g(y) \wedge \text{arg}_2(z_e, y_a)}$$

$$\frac{}{\lambda z.\ \exists y.\ \text{acquired}(z_e) \wedge \text{Pixar}(y_a) \wedge \text{arg}_2(z_e, y_a)}$$

Dependencies to Logical Forms

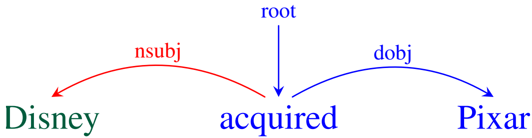
Composition



$$\frac{(\textbf{dobj}\quad \textbf{acquired}\qquad \textbf{Pixar})}{\lambda z.\ \exists y.\ \text{acquired}(z_e) \wedge \text{Pixar}(y_a) \wedge \text{arg}_2(z_e, y_a)}$$

Dependencies to Logical Forms

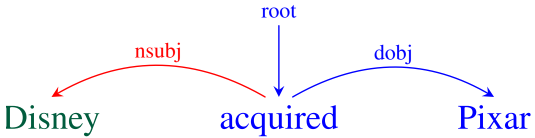
Composition



$$
\begin{array}{cccc}
(\textcolor{red}{\textbf{nsubj}} & (\textcolor{blue}{\textbf{dobj}} \quad \textcolor{blue}{\textbf{acquired}} \quad \textcolor{blue}{\textbf{Pixar}}) & \textbf{Disney}) \\
\lambda f g z.\ \exists x. & \underline{\hphantom{\lambda z.\ \exists y.\ \mathrm{acquired}(z_e) \wedge \mathrm{Pixar}(y_a)}} & \lambda x.\mathrm{Disney}(x_a) \\
f(z) \wedge g(x) \wedge & \lambda z.\ \exists y.\ \mathrm{acquired}(z_e) \wedge \mathrm{Pixar}(y_a) & \\
\mathrm{arg}_1(z_e, x_a) & \wedge\ \mathrm{arg}_2(z_e, y_a) &
\end{array}
$$

Dependencies to Logical Forms

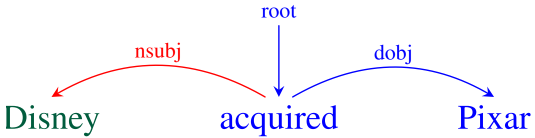
Composition



$$
\dfrac{
\begin{array}{c}(\textbf{nsubj} \\ \lambda f g z.\ \exists x. \\ f(z) \wedge g(x) \wedge \\ \mathrm{arg}_1(z_e, x_a)\end{array}
\quad
\dfrac{(\textbf{dobj} \quad \textbf{acquired} \quad \textbf{Pixar})}{\begin{array}{c}\lambda z.\ \exists y.\ \mathrm{acquired}(z_e) \wedge \mathrm{Pixar}(y_a) \\ \wedge\ \mathrm{arg}_2(z_e, y_a)\end{array}}
}{
\begin{array}{c}\lambda g z. \exists x y. \mathrm{acquired}(z_e) \wedge \mathrm{Pixar}(y_a) \wedge \mathrm{g}(x) \wedge \\ \mathrm{arg}_1(z_e, x_a) \wedge \mathrm{arg}_2(z_e, y_a)\end{array}
}
\qquad
\begin{array}{c}\textbf{Disney}) \\ \lambda x.\mathrm{Disney}(x_a)\end{array}
$$

Dependencies to Logical Forms

Composition



(nsubj (dobj acquired Pixar) Disney)

$$\text{nsubj}: \lambda f g z.\ \exists x.\ f(z) \wedge g(x) \wedge \text{arg}_1(z_e, x_a)$$

$$\text{(dobj acquired Pixar)}: \lambda z.\ \exists y.\ \text{acquired}(z_e) \wedge \text{Pixar}(y_a) \wedge \text{arg}_2(z_e, y_a)$$

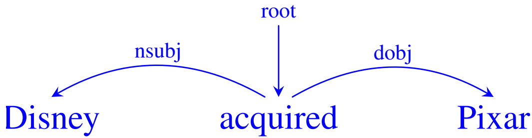
$$\text{Disney}: \lambda x.\text{Disney}(x_a)$$

$$\lambda g z.\exists x y.\text{acquired}(z_e) \wedge \text{Pixar}(y_a) \wedge \text{g}(x) \wedge \text{arg}_1(z_e, x_a) \wedge \text{arg}_2(z_e, y_a)$$

$$\lambda z.\exists x y.\text{acquired}(z_e) \wedge \text{Pixar}(y_a) \wedge \text{Disney}(x_a) \wedge \text{arg}_1(z_e, x_a) \wedge \text{arg}_2(z_e, y_a)$$

Dependencies to Logical Forms

Composition



$$\frac{(\textbf{nsubj} \quad (\textbf{dobj} \quad \textbf{acquired} \quad \textbf{Pixar}) \quad \textbf{Disney})}{\begin{array}{c}\lambda z.\exists xy.\text{acquired}(z_e) \wedge \text{Pixar}(y_a) \wedge \text{Disney}(x_a) \wedge \\ \text{arg}_1(z_e, x_a) \wedge \text{arg}_2(z_e, y_a)\end{array}}$$

Dependencies to Logical Forms

Disney $\xrightarrow{\text{appos}}$ the company

$$\textit{appos} = \lambda fgx. f(x) \wedge g(x)$$

company $\xrightarrow{\text{partmod}}$ located in CA

$$\textit{partmod} = \lambda fgx. \exists z. f(x) \wedge g(z) \wedge \mathsf{arg}_2(z_e, x_a)$$

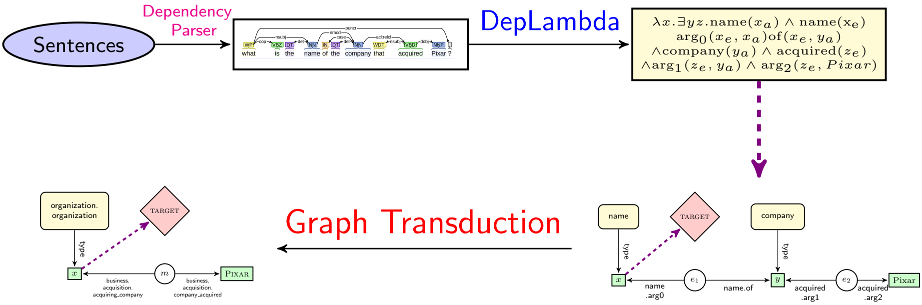
Disney $\xrightarrow{\text{conj}}$ and Pixar

$$\textit{conj} = \lambda fgz. \exists xy. f(x) \wedge g(y) \wedge \mathrm{coord}(z, x, y)$$

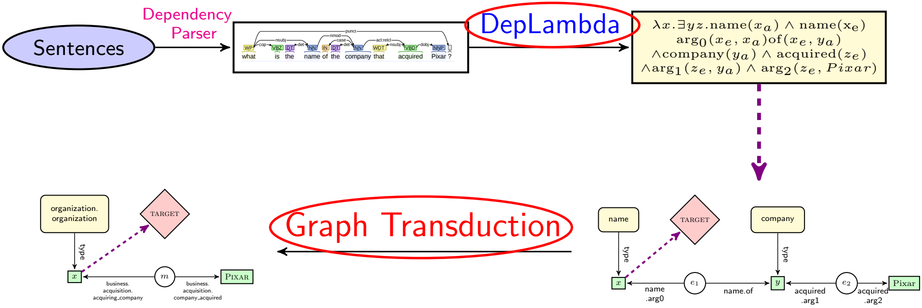
Comparison with CCG

CCG	DepLambda
Lexicalized semantics S\NP/NP : $\lambda f_2 f_1 x. \exists yz. \text{acquired}(x) \land f_1(y) \land f_2(z) \land \text{arg}_1(x,y) \land \text{arg}_2(x,z)$	Simple lexical semantics $\lambda x. \text{acquired}(x_e)$
Words drive composition	Dependencies drive composition
Argument adjunct distinction $S\backslash NP/PP/NP$ vs. $(S\backslash NP)\backslash(S\backslash NP)/NP$	Every dependent is an adjunct
With "complex types" comes power $(S[dcl]\backslash NP)/(S[to]\backslash NP_{\mathbf{x}})/NP_{\mathbf{x}}$	Hard time for few constructions

Freebase Semantic Parsing [Reddy et al., 2014]



Freebase Semantic Parsing [Reddy et al., 2014]



Baselines

SimpleGraph: All entities connected to a single event

- Does not handle compositional questions

CCGGraph: CCG logical forms

DepTree: Directly transduce a dependency tree to target graph

Baselines

SIMPLEGRAPH: All entities connected to a single event

- Does not handle compositional questions

CCGGRAPH: CCG logical forms

DEPTREE: Directly transduce a dependency tree to target graph

Baselines

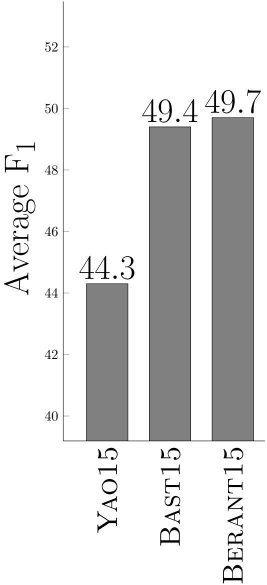
SIMPLEGRAPH: All entities connected to a single event

- Does not handle compositional questions

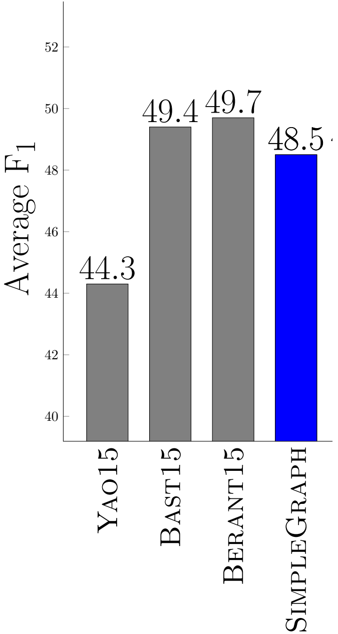
CCGGRAPH: CCG logical forms

DEPTREE: Directly transduce a dependency tree to target graph

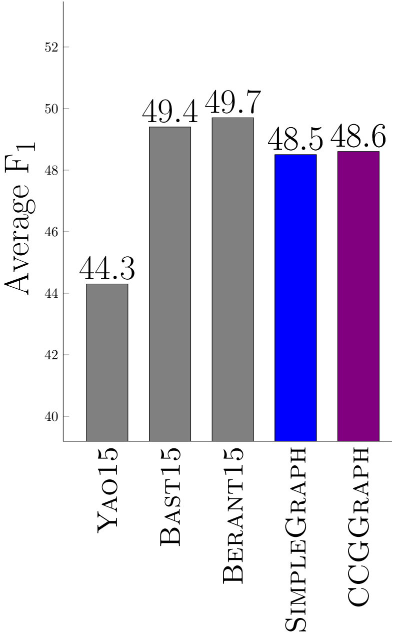
Results on WebQuestions



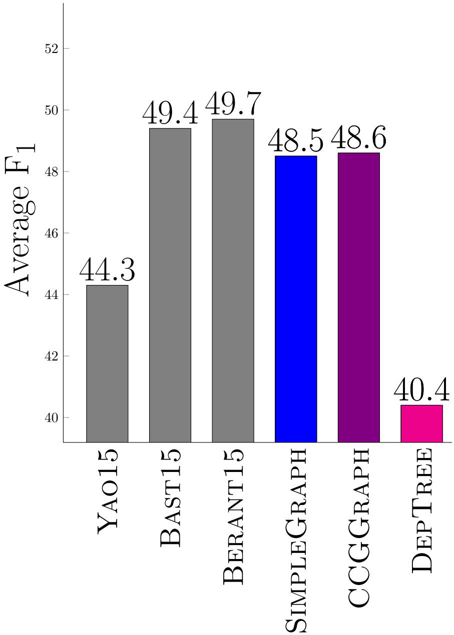
Results on WebQuestions



Results on WebQuestions



Results on WebQuestions



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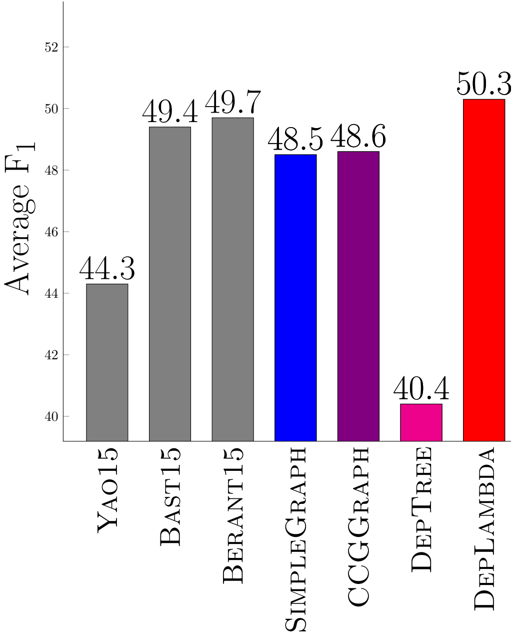

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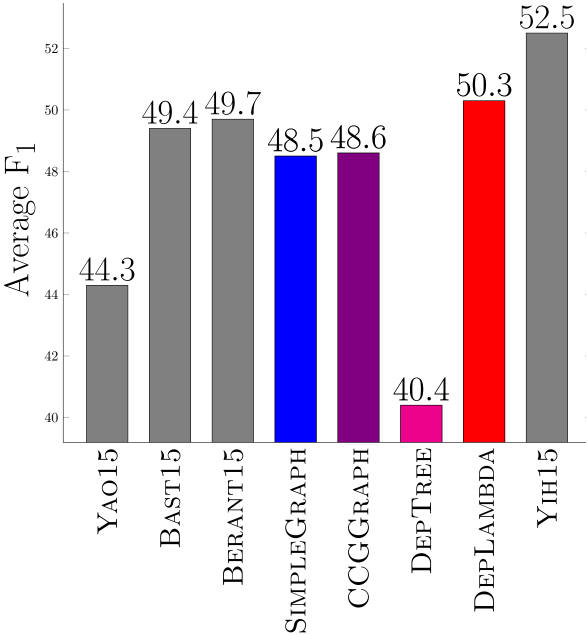
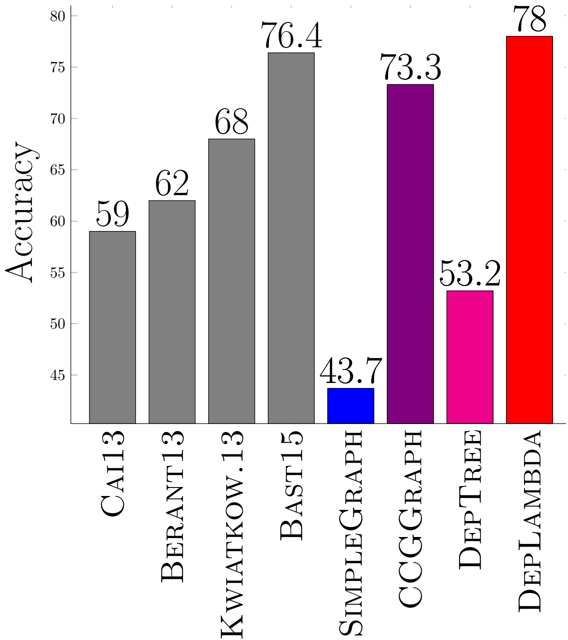
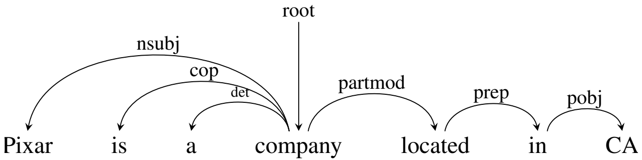


Results on Free917



Recap



$\ldots > \text{dobj} > \cdots > \text{nsubj} > \ldots$

(*partmod*	company	(*prep*	located	(*pobj*	in	CA)
$\lambda fgx.\exists z.$ $f(x) \wedge g(z) \wedge$ $\text{arg}_2(z_e, x_a)$	$\lambda x.\text{compay}(x_a)$	$\lambda fgz.$ $f(z) \wedge g(z)$	$\lambda x.\text{located}(x_e)$	$\lambda fgz.\exists x.$ $f(z) \wedge g(x)$ $\text{arg}_{\text{in}}(z_e, x_a)$	$\lambda x.\text{empty}(x)$	$\lambda x.\text{CA}(x_a)$

lambda expression composition

$$\exists z.\text{company}(\text{Pixar}) \wedge \text{located}(z_e) \wedge \text{arg}_2(z_e, \text{Pixar}) \wedge \text{arg}_{\text{in}}(z_e, \text{CA})$$

Summary

- Lambda Calculus for converting Dependencies to Logical Forms
- Semantic parsing as Graph Transduction
- State-of-the-art results on Free917 and competitive results on WebQuestions
- Work in progress: DepLambda for multiple languages

Rules available from

https://github.com/sivareddyg/deplambda

Thank You!

Summary

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Learning Model

Structured Perceptron: Ranks a pair of grounded and ungrounded graph

$$(\hat{g}, \hat{u}) = \arg\max_{g,u} \Phi(g, u, q, KB) \cdot \theta$$

Features: Φ is defined over sentence, grounded and ungrounded graph

Training: Use a surrogate graph (dynamic oracle) to update weights

$$\theta \leftarrow \theta + \Phi(g^+, u^+, q, KB) - \Phi(\hat{g}, \hat{u}, q, KB)$$

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Learning Model

Oracle Graphs: Search for all the grounded graphs reachable via the ungrounded graph.

Pick all the graphs with minimal F_1-loss against the gold answer.

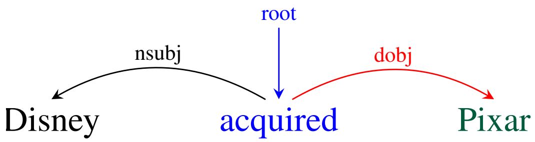
Surrogate Gold Graph:

$$(u^+, g^+) = \operatorname*{arg\,max}_{(u,g) \in O_{KB,A}(q)} \theta^t \cdot \Phi(u, g, q, KB),$$

Beam Search: Limit the predictions to 100 graph pairs, and choose the best prediction for update.

Dependencies to Logical Forms

Single Type System

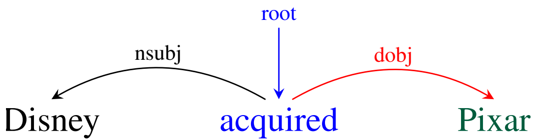


All constituents are of the same lambda expression type

TYPE[acquired] = **TYPE**[Pixar] = **TYPE**[(dobj acquired Pixar)]

Dependencies to Logical Forms

Single Type System

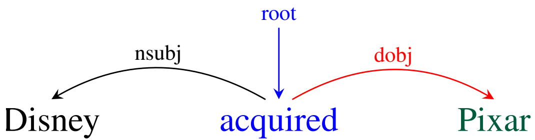


All **words** have a *lambda expression* of type η

- **TYPE**[acquired] = η
- **TYPE**[Pixar] = η
- **TYPE**[(dobj acquired Pixar)] = η

Dependencies to Logical Forms

Single Type System



All **constituents** have a *lambda expression* of type η

- **TYPE**[acquired] = η
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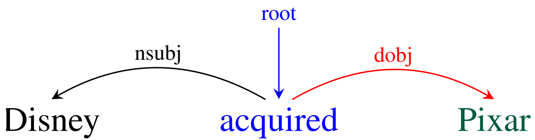
Dependencies to Logical Forms

Single Type System



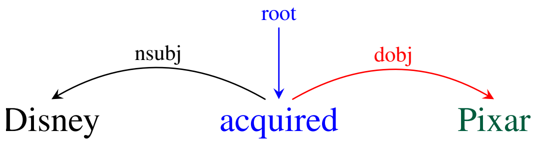
All constituents have a *lambda expression* of type η

- **TYPE**[acquired] = η
- **TYPE**[Pixar] = η
- **TYPE**[(dobj acquired Pixar)] = η

$\Longrightarrow$ **TYPE**[dobj] = $\eta \rightarrow \eta \rightarrow \eta$

Dependencies to Logical Forms

Lambda Calculus for Single Type System

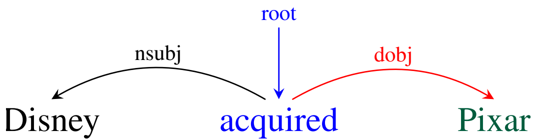


Lambda Expression for words

$$\text{acquired} \Rightarrow \lambda x_e.\,\mathsf{acquired}(x_e)$$
$$\text{Pixar} \Rightarrow \lambda x_a.\,\mathsf{Pixar}(x_a)$$

Dependencies to Logical Forms

Lambda Calculus for Single Type System



Lambda Expression for words

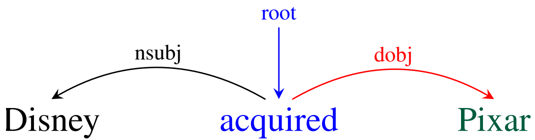
$$\text{acquired} \Rightarrow \lambda x_e.\,\text{acquired}(x_e) \qquad \Rightarrow \textbf{TYPE} = \textbf{Event} \rightarrow \textbf{Bool}$$

$$\text{Pixar} \Rightarrow \lambda x_a.\,\text{Pixar}(x_a) \qquad \Rightarrow \textbf{TYPE} = \textbf{Ind} \rightarrow \textbf{Bool}$$

Here **TYPE**[acquired] $\neq$ **TYPE**[Pixar] ✗

Dependencies to Logical Forms

Lambda Calculus for Single Type System



Lambda Expression for words

acquired $\Rightarrow \lambda \mathbf{x_a} x_e.\mathrm{acquired}(x_e)$

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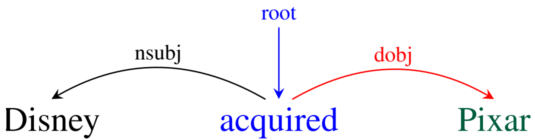
Dependencies to Logical Forms

Lambda Calculus for Single Type System



Lambda Expression for words

$$\text{acquired} \Rightarrow \lambda \mathbf{x_a} x_e.\,\text{acquired}(x_e) \quad \Rightarrow \textbf{TYPE} = \textbf{Ind} \times \textbf{Event} \rightarrow \textbf{Bool}$$

$$\text{Pixar} \Rightarrow \lambda x_a \mathbf{x_e}.\,\text{Pixar}(x_a) \quad \Rightarrow \textbf{TYPE} = \textbf{Ind} \times \textbf{Event} \rightarrow \textbf{Bool}$$

Here η = **TYPE**[acquired] = **TYPE**[Pixar] ✓

Lambda calculus for "*Single Type*" System

More dependency labels

- (appos Disney the_company)

$$\textit{appos} = \lambda fgx.f(x) \wedge g(x)$$

This function unifies two nodes

- (partmod a_company acquired_by_Disney)

$$\textit{partmod} = \lambda fgx.\exists z.f(x) \wedge g(z) \wedge \mathrm{arg}_1(z_e, x_a)$$

This function reverses the dependency arc direction, but still returns the head

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$$conj = \lambda fgz. \exists xy. f(x) \wedge g(y) \wedge \textbf{coord}(z, x, y)$$

This function creates a struct with two variables

- (rcmod Disney which_acquired_Pixar)

(rcmod Disney
(wh-dobj (BIND f (nsubj (dobj acquired f) Pixar))
which))

Lambda calculus for "*Single Type*" System

More dependency labels

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This function creates a struct with two variables

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$$
\begin{array}{l}
(\text{rcmod Disney} \\
\qquad (\text{wh-dobj } (\textsf{BIND}\, f \ (\text{nsubj } (\text{dobj acquired}\, f) \text{ Pixar})) \\
\qquad\qquad \text{which}))
\end{array}
$$

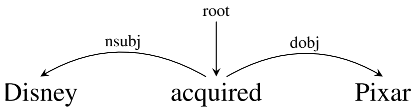
CCG to Logical Forms

Steedman, 2000, 2012; Bos et al., 2004; Lewis & Steedman, 2013; Reddy et al., 2014

$$
\begin{array}{ccc}
\text{Disney} & \text{acquired} & \text{Pixar} \\
\hline
NP & S\backslash NP/NP & NP \\
\text{Disney} & \begin{array}{c}\lambda y \lambda x.\exists e.\ \text{acquired}(e) \\ \wedge\ \text{arg}_1(e,x) \\ \wedge\ \text{arg}_2(e,y)\end{array} & \text{Pixar} \\
\cline{2-3}
 & \multicolumn{2}{c}{S\backslash NP \quad >} \\
 & \multicolumn{2}{c}{\begin{array}{c}\lambda x.\exists e.\ \text{acquired}(e) \\ \wedge\ \text{arg}_1(e,x) \wedge\ \text{arg}_2(e,\text{Pixar})\end{array}} \\
\hline
\multicolumn{3}{c}{S \quad <} \\
\multicolumn{3}{c}{\exists e.\ \text{acquired}(e) \wedge \text{arg}_1(e,\text{Disney}) \wedge \text{arg}_2(e,\text{Pixar})}
\end{array}
$$

Dependencies to Logical Forms

Challenges



The obvious idea

if *proper noun* **then**
  assign $\lambda x.\mathrm{word}(x)$
else if *verb* with *subject* and *object* **then**
  assign $\lambda fge.\exists xy.f(x) \wedge g(y) \wedge \mathrm{word}(e) \wedge \mathrm{arg}_1(e,x) \wedge \mathrm{arg}_2(e,y)$
end if

Dependencies to Logical Forms

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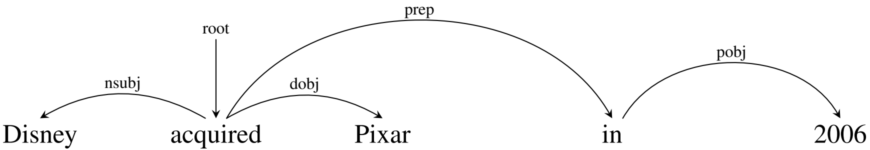

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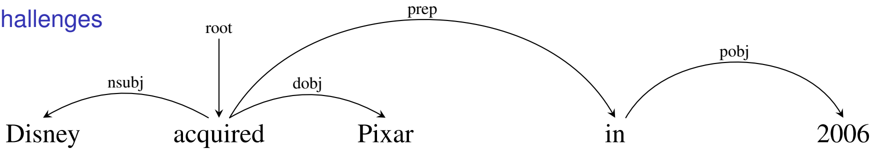
end if

But, what about?

Dependencies to Logical Forms

Challenges



Problems

1. Rules $\propto$ dependency label permutations
2. Complex lexical semantics
3. Highly sensitive to parse errors
4. Prone to type collisions

Comparison with CCG

Handling of control verbs is painful.

Sentence:
John persuaded Jim to acquire Pixar.

Binarized Tree:
(nsubj (xcomp (dobj persuaded Jim) to_acquire_Pixar) John)

Elegant handling in CCG
persuaded: $((S[dcl]\backslash NP)/(S[to]\backslash NP_x))/NP_x$

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Conjunctions

Sentence:

Eminem signed to Interscope and discovered 50 Cent.

Binarized tree:

(nsubj (conj-vp (cc s_to_I and) d_50) Eminem)

Substitution:

conj-vp $\Rightarrow \lambda fgx.\exists yz.f(y) \wedge g(z) \wedge \mathrm{coord}(x,y,z)$

Logical Expression:

$$\lambda w.\exists xyz.\mathrm{Eminem}(x_a) \wedge \mathrm{coord}(w,y,z) \wedge \mathrm{arg}_1(w_e,x_a) \wedge \mathrm{s\_to\_I}(y) \wedge \mathrm{d\_50}(z)$$

Post processing:

$$\lambda e.\exists xyz.\mathrm{Eminem}(x_a) \wedge \mathrm{arg}_1(y_e,x_a) \wedge \mathrm{arg}_1(z_e,x_a) \wedge \mathrm{s\_to\_I}(y) \wedge \mathrm{d\_50}(z)$$

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Relative Clause

following Moortgat (1988); Pereira (1990); Carpenter (1998)

Sentence:

Apple which Jobs founded

Binarized tree:

$$(\text{rcmod Apple} \\ (\text{wh-dobj } (\text{BIND } f \ (\text{nsubj } (\text{dobj founded } f) \text{ Jobs})) \\ \text{which}))$$

Substitution:

wh-dobj $\Rightarrow \lambda fgz.f(z)$
rcmod $\Rightarrow \lambda fgz.f(z) \wedge g(z)$

Logical Expression:

$$\lambda u. \exists xy. \text{founded}(x_e) \wedge \text{Jobs}(y_a) \\ \wedge \text{arg}_1(x_e, y_a) \wedge \text{arg}_2(x_e, u_a) \wedge \text{Apple}(u_a)$$

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Expressivity

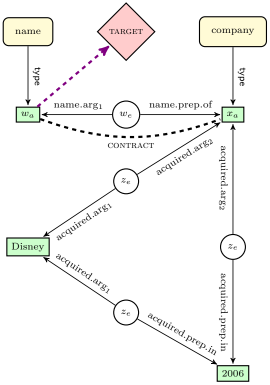
How isomorphic are the representations compared to Knowledge Graph?
Average Oracle F_1 Table.

Search Space

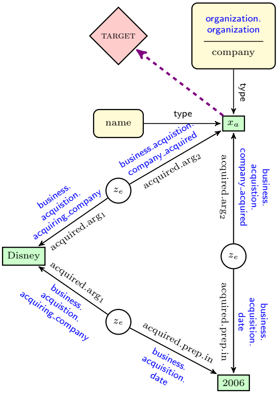
How many ways to reach an answer?
Average Oracle F_1 Table.

Graph Transformation: CONTRACT operation

What is the name of the company which Disney acquired in 2006?



Ungrounded graph



Grounded graph

Graph Mismatch: EXPAND operation

What to do Washington DC December?

Before EXPAND

- $\lambda z. \exists xyw. \text{TARGET}(x_a) \wedge \text{do}(z_e) \wedge \text{arg}_1(z_e, x_a) \wedge \text{Washington\_DC}(y_a) \wedge \text{December}(w_a)$

After EXPAND

- $\lambda z. \exists xyw. \text{TARGET}(x_a) \wedge \text{do}(z_e) \wedge \text{arg}_1(z_e, x_a) \wedge \text{Washington\_DC}(y_a) \wedge \text{dep}(z_e, y_a) \wedge \text{December}(w_a) \wedge \text{dep}(z_e, w_a)$