A Simple Approach to Case-Based Reasoning in Knowledge Bases

Rajarshi Das
Ameya Godbole
Shehzaad Dhuliawala
Manzil Zaheer
Andrew McCallum

1 UMass Amherst
College of Information & Computer Sciences

3 Google Research

2 Microsoft Research
Automated Reasoning
Automated Reasoning

- Ability to infer \textit{new facts} from \textit{observed evidence}.
Automated Reasoning

• Ability to infer *new facts* from *observed evidence*.

• Knowledge Bases (KBs) provide an excellent test bed for automated reasoning
Automated Reasoning
Automated Reasoning

United States

Amherst, Massachusetts

University of Massachusetts Amherst

Andrew McCallum

University of Massachusetts Amherst

Research

The main goal of my research is to dramatically increase our ability to mine actionable knowledge from unstructured text. I am especially interested in information extraction from the Web and text mining, co-reference resolution, causal models of text and data mining—toward probabilistic approaches and graphical models. For more information see our current projects and publications.
Automated Reasoning

Information Extraction

Open Review

created

Andrew McCallum

research_interest

works_at

UMass Amherst

located

Amherst

country_of_location

United States

citizen

ML&Friends Lunch

organizes

India

grad_student_of

Rajarshi Das

India

works_at

located

United States

works_at
Automated Reasoning
lives_in_country(a, d) ⇐ works_at(a, b) ^ located(b, c) ^ country_of_location(c, d)
lives_in_country(a, d) ⇐ works_at(a, b) ^ located(b, c) ^ country_of_location(c, d)
Automated Reasoning

\[
lives_{in\_country}(a, d) \iff works_{at}(a, b) \land located(b, c) \land country_{of\_location}(c, d)
\]
Automated Reasoning

Information Extraction

ML & Friends Lunch

Open Review

Andrew McCallum

Rajarshi Das

UMass Amherst

Amherst

United States

India

lives_in_country(a, d) ⇐ works_at(a, b) ^ located(b, c) ^ country_of_location(c, d)

works_at(x, z) ⇐ grad_student_of(x, y) ^ works_at(y, z)
Automated Reasoning

Information Extraction

Open Review

created

works_at

Andrew McCallum

UMass Amherst

located

Amherst

country_of_location

United States

citizen

works_at??

India

organizes

ML&Friends Lunch

research_interest

grad_student_of

works_at

Rajarshi Das

works_at(x, z) ⇐ grad_student_of(x, y) ^ works_at(y, z)

lives_in_country(a, d) ⇐ works_at(a, b) ^ located(b, c) ^ country_of_location(c, d)

store rules for logical inference in the model parameters.

- (Lao, Mitchell, Cohen EMNLP 2011)
- (Neelakantan, Roth, McCallum ACL 2015)
- (Das, Neelakantan, Belanger, McCallum EACL 2017)
- (Rocktäschel and Riedel Neurips 2017)
- (Xiong, Hoang, Wang EMNLP 2017)
- (Das, Dhuliawala, Zaheer, Vilnis, et al. ICLR 2018)
- (Lin, Socher, Xiong EMNLP 2018)
- (Minervini, Bošnjak, Rocktäschel, Riedel, Grelenstette AAAI 2020)
Contextual Reasoning

Information Extraction

Open Review

created

works_at

Andrew McCallum

UMass Amherst

located

Amherst

research_interest

ML & Friends Lunch

organizes

Rajarshi Das

grad_student_of

citizen

India

lives_in_country

country_of_location

United States
Do I need visa for traveling to AKBC 2021??
Do I need visa for traveling to AKBC 2021??

(Raj, needs_visa_for_countries, ?)
Do I need visa for traveling to AKBC 2021??

\[(Raj, \text{needs\_visa\_for\_countries, } ?)\]
Do I need visa for traveling to AKBC 2021??

(Raj, needs_visa_for_countries, ?)

Andrew McCallum works at UMass Amherst located in Amherst, Massachusetts, United States.

Rajarshi Das is a citizen of India and lives in India.

Brazil, Colombia, Egypt, UK, ...

No visa required for diplomats from Brazil, Colombia, Egypt, UK, ...

Contextual Reasoning
Do I need visa for traveling to AKBC 2021??

(Raj, needs_visa_for_countries, ?)

Andrew McCallum works at UMass Amherst located in Amherst, United States. Rajarshi Das is a citizen of India.

Brazil, Colombia, Egypt, UK, ...

Malaysia, Thailand, Fiji, Guyana, ...

no_visa_required_for_diplomats visa_on_arrival
Do I need visa for traveling to AKBC 2021??

(Raj, needs_visa_for_countries, ?)

Andrew McCallum
- works_at: UMass Amherst
- located: Amherst

Rajarshi Das
- citizen: India
- lives_in_country: United States

United States
- country_of_location:

Common-Wealth
- member:
  - Brazil, Colombia, Egypt, UK, ...
  - Malaysia, Thailand, Fiji, Guyana, ...
  - UK, Canada, Pakistan

no_visa_required_for_diplomats

visa_on_arrival

member

contextual_reasoning
Do I need visa for traveling to AKBC 2021? 

(Raj, needs_visa_for_countries, ?) 

Andrew McCallum 
works_at 
UMass Amherst 
located 
Amherst 

Rajarshi Das 
citizen 
India 
lives_in_country 
United States 
country_of_location 

Brazil, Colombia, Egypt, UK, ... 
no_visa_required_for_diplomats 

Malaysia, Thailand, Fiji, Guyana, ... 
visa_on_arrival 

Common-Wealth 
member 

UK, Canada, Pakistan 
member 

Contextual Reasoning
Do I need visa for traveling to AKBC 2021? (Raj, needs_visa_for_countries, ?)

- no_visa_required_for_diplomats
  - Brazil, Colombia, Egypt, UK, ...
  - Malaysia, Thailand, Fiji, Guyana, ...
  - UK, Canada, Pakistan
  - Canada, Mexico
  - Venezuela

- Schengen countries
  - France, Italy, Spain

- Contextual Reasoning
  - Canada, Mexico
  - Schengen countries
  - France, Italy, Spain
  - member
  - neighbor
  - no_visa_for_diplomats
  - member
  - visas_on_arrival
  - member
  - member
  - member

- United States
  - located
  - Amherst
  - citizen
  - citizen
  - works_at
  - UMass Amherst
  - works_at
  - Amherst

- Rajarshi Das
  - citizen
  - India
  - located
  - United States
  - member
  - Common-Wealth
  - member
  - member
  - member
  - member
  - member
United States
Andrew McCallum
works_at
UMass Amherst
located
Amherst

Rajarshi Das
citizen
India

Andrew needs visa for countries, ?

no_visa_required_for_diplomats
Brazil, Colombia, Egypt, UK, ...

visa_on_arrival
Malaysia, Thailand, Fiji, Guyana, ...

United States
country_of_location
Common-Wealth
member
Schengen countries
country_of_location
Canada, Mexico

member_annex-ii_countries
Malaysia, Thailand, Fiji, Guyana, ...

member
UK, Canada, Pakistan

member
Brazil, Colombia, Egypt, UK, ...

member
Canada, Mexico

member
France, Italy, Spain

France
no_visa_for_diplomats
Venezuela

Italy
member
Spain

Contextual Reasoning

New Foreign Policy??
Country X, Y...
Do I need visa for traveling to AKBC 2021? 

(Raj, needs_visa_for_countries, ?) 

no_visa_required_for_diplomats 

Brazil, Colombia, Egypt, UK, ... 

Malaysia, Thailand, Fiji, Guyana, ... 

Common-Wealth 

Canada, Mexico 

Venezuela 

France, Italy, Spain 

Schengen countries 

United States 

Amherst 

Andrew McCallum works_at UMass Amherst located Amherst 

Rajarshi Das citizen India 

India located United States 

United States lived_in_country Rajarshi Das 

Rajarshi Das grad_student_of Andrew McCallum 

Andrew McCallum located United States 

United States lives_in_country Rajarshi Das 

Country X, Y... 

New Foreign Policy??

Contextual Reasoning 

- Different fine-grained rule for each entity 
- Hard to store all of them in parameters 
- Unclear how parameters will adapt with changing data
Contextual Reasoning

- Different fine-grained rule for each entity
- Hard to store all of them in parameters
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Contextual Reasoning

- Different fine-grained rule for each entity
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This Work

- Learn fine-grained rules tailored for each entity
Contextual Reasoning

- Different fine-grained rule for each entity
- Hard to store all of them in parameters
- Unclear how parameters will adapt with changing data

This Work

- Learn fine-grained rules tailored for each entity
- Derive logical rules dynamically from "contextual entities" rather than storing in parameters
Contextual Reasoning

• Different fine-grained rule for each entity
• Hard to store all of them in parameters
• Unclear how parameters will adapt with changing data

This Work

• Learn fine-grained rules tailored for each entity
• Derive logical rules dynamically from “contextual entities” rather than storing in parameters
• In fact, other than entity embeddings we have “no parameters!”
Contextual Reasoning

• Different fine-grained rule for each entity
• Hard to store all of them in parameters
• Unclear how parameters will adapt with changing data

This Work

• Learn fine-grained rules tailored for each entity
• Derive logical rules dynamically from “contextual entities” rather than storing in parameters
• In fact, other than entity embeddings we have “no parameters!”
• Since rules are derived at inference, can handle updates seamlessly.
Case-Based Reasoning (Schank 1982; Kolodner 1983)

- Process of solving new problems based on solution to similar past problems.
Case-Based Reasoning (Schank 1982; Kolodner 1983)

- Process of solving new problems based on solution to similar past problems.
Case-Based Reasoning (Schank 1982; Kolodner 1983)

- Process of solving new problems based on solution to similar past problems.

A case is an abstract representation of a (past) problem and its solution.
Case-Based Reasoning (Schank 1982; Kolodner 1983)

- Process of solving new problems based on solution to similar past problems.

4 step process:

A case is an abstract representation of a (past) problem and its solution.
Case-Based Reasoning *(Schank 1982; Kolodner 1983)*

- Process of solving new problems based on solution to similar past problems.

4 step process:

i) Retrieve: Given a new problem, retrieve the relevant cases from memory.

A case is an abstract representation of a (past) problem and its solution.
Case-Based Reasoning (Schank 1982; Kolodner 1983)

- Process of solving new problems based on solution to similar past problems.

4 step process:

i) Retrieve: Given a new problem, retrieve the relevant cases from memory.

ii) Reuse: the solutions to the previous case, if possible.

iii) Revise: the solutions, if necessary

iv) Retain: If the solution is successful, retain it in the memory.

A case is an abstract representation of a (past) problem and its solution.
Case-Based Reasoning in Knowledge Bases

How do we represent a case?

- Andrew McCallum
- Shib
- UMass Amherst
- EMNLP 2018
- India
- UK
- Common-wealth
- Belgium
- works_at
- grad_student_of
- citizen
- visa_required
- published
- held_in
- member
- member
- no_visa_required
- for_diplomats
- trades_with
- UK
- EMNLP 2018
- Belgium
- Common-wealth
- Andrew McCallum
- Shib
- UMass Amherst
Case-Based Reasoning in Knowledge Bases

How do we represent a case?

Andrew McCallum

grad_student_of

works_at

UMass Amherst

India

citizen

visa_required

UK

published

EMNLP 2018

held_in

Belgium

Commonwealth

member

no_visa_required_for_diplomats

member-1

trades_with

EMNLP 2018

Belgium

Andrew McCallum

grad_student_of

works_at

UMass Amherst

India

citizen

visa_required

UK

published

EMNLP 2018

held_in

Belgium

Commonwealth

member

no_visa_required_for_diplomats

member-1

trades_with

EMNLP 2018

Belgium
Case-Based Reasoning in Knowledge Bases

How do we represent a case?
Case-Based Reasoning in Knowledge Bases

How do we represent a case?

Andrew McCallum

grad_student_of

works_at

UMass Amherst

India

citizen

visa_required

United Kingdom

member

no_visa_required_for_diplomats

Commonwealth

member^{-1}

EMNLP 2018

published

Belgium

held_in

trades_with

India

Citizen

India

No Visa Required for Diplomats

Commonwealth

Member

EMNLP 2018

Published

Belgium

Held In

Trades With
A case in a KB is represented by:

- Shib
  - visa_required
  - published: EMNLP 2018

- UK

- India
  - citizen
  - no_visa_required for_diplomats

- Common-wealth
  - member

- Belgium
  - trades_with

- EMNLP 2018
  - held_in
Case-Based Reasoning in Knowledge Bases

A case in a KB is represented by:

(i) Fact (e1, r, e2)
Case-Based Reasoning in Knowledge Bases

A case in a KB is represented by:

(i) Fact (e1, r, e2)

(ii) Paths connecting e1 and e2

(i) Fact (e1, r, e2)

(ii) Paths connecting e1 and e2

Shib \(\rightarrow\) visa_required \(\rightarrow\) UK

India

citizen

India

member

Commonwealth

citizen

EMNLP 2018

published

Belgium

trades_with

Belgium

held_in

Commonwealth

member-1

India

no_visa_required_for_diplomats
Case-Based Reasoning in Knowledge Bases
Case-Based Reasoning in Knowledge Bases
Case-Based Reasoning in Knowledge Bases

(Raj, needs_visa_for, ?)
Case-Based Reasoning in Knowledge Bases

(Raj, needs_visa_for, ?)

1. Retrieve ‘K’ relevant cases from memory:
1. Retrieve ‘K’ relevant cases from memory:

(Raj, needs_visa_for, ?)

- Shib needs_visa_for UK
- India citizen
- no_visa_required_for_diplomats
- Common-wealth member
- EMNLP 2018
- Belgium held_in trades_with
Case-Based Reasoning in Knowledge Bases

(Raj, needs_visa_for, ?)

1. Retrieve ‘K’ relevant cases from memory:

- Shib: needs_visa_for, India, citizen, no_visa_required_for_diplomats, UK, published, EMNLP 2018, held_in, Belgium, trades_with
- Trapit: needs_visa_for, Italy, citizen, no_visa_required_for_diplomats, India, Germany, member, EU, member-1
Case-Based Reasoning in Knowledge Bases

(Raj, needs_visa_for, ?)

Revise

X

- citizen
- no_visa_required_for_diplomats

Y

- citizen
- member

A

- published
- held_in

B

- trades_with

P

- needs_visa_for
- member

Q

- member

Z

- member

count=2

count=1

count=1

count=1
Case-Based Reasoning in Knowledge Bases

(Raj, needs_visa_for, ?)

Revise

X (citizen) \rightarrow \text{no_visa_required_for_diplomats} \rightarrow \text{count}=2

Y (citizen) \rightarrow \text{member} \rightarrow \text{Z (member)} \rightarrow \text{count}=1

A (published) \rightarrow \text{held_in} \rightarrow B (trades_with) \rightarrow \text{count}=1

P (needs_visa_for) \rightarrow \text{member} \rightarrow Q (member) \rightarrow \text{count}=1

Reuse

Andrew McCallum

grad_student_of \rightarrow Rajarshi Das \rightarrow citizen \rightarrow India

works_at \rightarrow UMass Amherst

Brazil, Colombia, Egypt, UK, ... \rightarrow no_visa_required_for_diplomats

Malaysia, Thailand, Fiji, Guyana, ... \rightarrow visa_on_arrival

CommonWealth (member) \rightarrow UK, Canada, Pakistan, ...

...
Case-Based Reasoning in Knowledge Bases

(Raj, needs_visa_for, ?)

Revise

- X: citizen
- Y: citizen
- A: published
- B: held_in
- P: member
- Q: member
- Z: member

Reuse

- Andrew McCallum: grad_student_of Rajarshi Das
- Rajarshi Das: citizen India
- UMass Amherst: works_at

- Brazil, Colombia, Egypt, UK, ...
- Malaysia, Thailand, Fiji, Guyana, ...
- UK, Canada, Pakistan, ...

- no_visa_required_for_diplomats
- visa_on_arrival
- member CommonWealth
Case-Based Reasoning in Knowledge Bases

(Raj, needs_visa_for, ?)

Revise

公民 X -> 公民 Y
发布 A -> 拥有 B
需要签证 P -> 公民 Q

Reuse

Andrew McCallum -> Rajarshi Das
公民 India -> 共同体

Brazil, Colombia, Egypt, UK, …
Malaysia, Thailand, Fiji, Guyana, …
UK, Canada, Pakistan, …
Case-Based Reasoning in Knowledge Bases

### Revise

- (Raj, needs_visa_for, ?)

#### Count
- **X**: no_visa_required_for_diplomats, count=2
- **Y**: member, count=1
- **Z**: member⁻¹, count=1
- **P**: needs_visa_for, count=1

#### Valid
- **X**: no_visa_required_for_diplomats
- **Z**: member⁻¹

#### Invalid
- **P**: needs_visa_for

### Reuse

- Andrew McCallum
  - grad_student_of: Rajarshi Das
  - works_at: UMass Amherst

- Rajarshi Das
  - citizen: India
  - no_visa_required_for_diplomats
  - visa_on_arrival

- CommonWealth
  - member

- Brazil, Colombia, Egypt, UK, ...
- Malaysia, Thailand, Fiji, Guyana, ...
- UK, Canada, Pakistan, ...
Case-Based Reasoning in Knowledge Bases

(Raj, needs_visa_for, ?)

Revise

- X: citizen
- Y: member
- A: published
- B: held_in
- P: needs_visa_for
- Z: member

Returned Answers
- Brazil, Colombia, Egypt, UK, ...
- UK, Canada, Pakistan, ...

Reuse

- Andrew McCallum
  - grad_student_of: Rajarshi Das
  - works_at: UMass Amherst

- Rajarshi Das: citizen
- India
  - no_visa_required_for_diplomats
  - visa_on_arrival
  - member

- CommonWealth
  - UK, Canada, Pakistan, ...

Brazil, Colombia, Egypt, UK, ...
Malaysia, Thailand, Fiji, Guyana, ...
UK, Canada, Pakistan, ...
Representing Entities

- Entities are represented as (sparse) vectors of neighboring relations.

```
Andrew McCallum
| research_interest  | 1 |
| works_at           | 1 |
| research_interest  | 1 |
| plays_for          | 0 |
| grad_student_of    | 1 |
| created            | 1 |
| located_in         | 0 |
```

Andrew McCallum
Representing Entities

• Entities are represented as (sparse) vectors of neighboring relations.
Representing Entities

- Entities are represented as (sparse) vectors of neighboring relations.

- Cosine similarity between entities
- We consider only those entities for which we observe the query relation.
Experiments

- Task: Knowledge Base Completion (e1, r, ?) or (?, r⁻¹, e2)

- Data:

|       | |V| | |R| | |E| |
|-------|---|---|---|---|---|
| NELL-995 | 75,492 | 200 | 154,213 |
| FB122    | 9,738  | 122  | 112,476 |
| WN18RR   | 40,943 | 11   | 93,003  |

- Baselines:
  - Parametric Rule Learning methods
    - MINERVA (Das, Dhuliawala, Zaheer, Vilnis, Krishnamurthy, Smola, McCallum ICLR 2018)
    - GNTPs (Minervini, Bošnjak, Rocktäschel, Riedel, Grefenstette AAAI 2020)
  - Embedding based methods:
    - RotatE (Sun, Deng, Nie, Tang ICLR 2019)
    - ConvE (Dettmers, Minervini, Stenetorp, Riedel AAAI 2018)
    - Complex (Trouillon, Welbl, Riedel, Gaussier, Bouchard ICML 2017)
    - DistMul (Yang, Yih, He, Gao, Deng ICLR 2015)
    - TransE (Bordes, Usunier, Garcia-Duran, Weston, Yakhnenko Neurips 2013)
NELL-995
<table>
<thead>
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<th></th>
<th>TransE</th>
<th>DistMult</th>
<th>ComplEx</th>
<th>ConvE</th>
<th>RotatE</th>
<th>GNTPs</th>
<th>CBR</th>
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<td>0.41</td>
<td>0.40</td>
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<td>0.44</td>
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<tr>
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<td>Hits@3</td>
<td>Hits@5</td>
<td>Hits@10</td>
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<td></td>
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<tr>
<td><strong>With Rules</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
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<tr>
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<td></td>
<td></td>
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<tr>
<td><strong>Without Rules</strong></td>
<td></td>
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<td>41.5</td>
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<tr>
<td>DistMult</td>
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<td>40.3</td>
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<td>41.3</td>
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<td>GNTPs</td>
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<td>31.3</td>
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<tr>
<td>CBR</td>
<td><strong>40.0</strong></td>
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<td></td>
<td></td>
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</tr>
</tbody>
</table>
Learned Rules

Relation Type in NELL-995

- **person_leads_org**
  - MINERVA: 377
  - CBR: 444

- **athlete_playsfor_team**
  - MINERVA: 195
  - CBR: 255

- **org_hq_city**
  - MINERVA: 118
  - CBR: 447

- **agent_belongs_to_org**
  - MINERVA: 72
  - CBR: 47

- **born_in**
  - MINERVA: 140
  - CBR: 118
Learned Rules

<table>
<thead>
<tr>
<th>Relation Type in NELL-995</th>
<th>MINERVA</th>
<th>CBR</th>
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<tbody>
<tr>
<td>person_leads_org</td>
<td>377</td>
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<tr>
<td>athlete_playsfor_team</td>
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<tr>
<td>born_in</td>
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<td>140</td>
</tr>
</tbody>
</table>

More number of fine-grained rules
Future Work

- We introduce a general framework of CBR for KB reasoning.

Future steps:

- Richer entity representation and similarity metric
- Better matching of paths using path embeddings
- Better Ranking of paths
- Considering subgraphs instead of paths as solution to cases.
Conclusion

• We introduce a new approach
  • that derives reasoning rules dynamically for each entity instead of storing them in model parameters

• Requires no training

• Outperform existing rule-induction methods and are comparable to existing embedding based approaches.

• Lot of exciting future directions.
Conclusion

- We introduce a new approach
  - that derives reasoning rules dynamically for each entity instead of storing them in model parameters
- Requires no training
- Outperform existing rule-induction methods and are comparable to existing embedding based approaches.
- Lot of exciting future directions.

Thank you!