Chains of Reasoning over Entities, Relations, and Text using Recurrent Neural Networks

Rajarshi Das, Arvind Neelakantan, David Belanger, Andrew McCallum

Presentation in Deep Learning Summer School, Montreal
Aug 4 2016
January 15, 2000
Tech pioneer Bill Gates stepped down today as chief executive officer of Microsoft, the Seattle-headquartered software giant. His long-time friend, Steve Balmer, will take over as CEO of Microsoft.
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Open IE textual relation types
(Banko et al, 2007)
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Union of all relation types from all structured sources and text

Open IE textual relation types

(Banko et al, 2007)
Universal Schema for Relation Extraction

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Union of all relation types from all structured sources and text

![Freebase](https://www.freebase.com)

**Freebase**
- **Freebase: CEO ?**
- **Freebase: worked_together ?**

**long-time friend**
**take over as**
**CEO**

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Chains of Reasoning for Relation Extraction

A Path between ‘Melinda’ and ‘Seattle’

- Microsoft
  - headquartered
  - Seattle

- Melinda
  - spouse
  - Bill
  - chairman
  - Microsoft
  - lives in??

- Seattle
  - headquartered
  - Multi-hop Inference
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- **Sherlock** (Schoenmackers et al. 2010)
- **Path Ranking Algorithm** (Lao et al, 2011, 2012),

\[ \text{Spouse}(A,B) \land \text{Chairman}(B,C) \land \text{HQ-in}(C,D) \rightarrow \text{Lives-in}(A,D) \]
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Symbolic; Doesn't generalize
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\text{Spouse}(A,B) \& \text{CEO}(B,C) \& \text{HQ-in}(C,D) \rightarrow \text{Lives-in}(A,D) \\
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**Chains of Reasoning for Relation Extraction**

- **Sherlock** (Schoenmackers et al. 2010)
- **Path Ranking Algorithm** (Lao et al, 2011, 2012),

Spouse(A,B) & Chairman(B,C) & HQ-in(C,D) → Lives-in(A,D)
Spouse(A,B) & CEO(B,C) & HQ-in(C,D) → Lives-in(A,D)
Spouse(A,B) & COO(B,C) & HQ-in(C,D) → Lives-in(A,D)

Symbolic; Doesn't generalize
RNNs for Chains of Reasoning

Melinda → Bill (spouse) → Microsoft (chairman) → Seattle (headquartered)
RNNs for Chains of Reasoning

Melinda spouse Bill chairman Microsoft headquartered Seattle
RNNs for Chains of Reasoning

Melinda  spouse  Bill  chairman  Microsoft  headquartered  Seattle
RNNs for Chains of Reasoning
RNNs for Chains of Reasoning
RNNs for Chains of Reasoning

Melinda → Bill → Microsoft → Seattle

spouse

chairman

headquartered

Seattle
RNNs for Chains of Reasoning

Vector representation of the path

RNN

spouse
Melinda

Bill

chairman

Microsoft

headquartered

Seattle
RNNs for Chains of Reasoning
RNNs for Chains of Reasoning

Melinda → spouse Bill
Bill → chairman Microsoft
Microsoft → headquarteried Seattle

similarity metric

lives in??
RNNs for Chains of Reasoning

- Melinda
- Bill
- Microsoft
- Seattle
- RNN
- spouse
- chairman
- headquartered
- similarity metric
- lives in??
- 0.94
RNNs for Chains of Reasoning

Logical Inference in Vector space!

Melinda \(\rightarrow\) Bill \(\rightarrow\) Microsoft \(\rightarrow\) Seattle

spouse \(\rightarrow\) chairman \(\rightarrow\) headquartered

0.94

similarity metric

lives in??
RNNs for Chains of Reasoning

Logical Inference in Vector space!

Melinda spouse Bill chairman Microsoft headquartered Seattle

similarity metric

Neelakantan et al’ 15

lives in??
Contributions
Contributions

Contributions


2. Combine evidence from multiple paths between entity pairs.
Contributions


2. Combine evidence from multiple paths between entity pairs.

3. Entity Aware RNN for chains of reasoning
Contributions


2. Combine evidence from multiple paths between entity pairs.

3. Entity Aware RNN for chains of reasoning

%MAP 64.43% ———— 73.26%

2. Combine evidence from multiple paths between entity pairs.

3. Entity Aware RNN for chains of reasoning

%MAP 64.43% 13.7% 73.26%

- **lives in??**
- **works in??**

Shared representations for relations

- All query relation vectors
- Single Composition Matrix for all query relations
- RNN
- RNN
- RNN
- Melinda spouse Bill
- chairman Microsoft
- headquartered Seattle
- similarity metric
- Shared representations for relations

Positive similarity metric: 0.94
Results
## Results

<table>
<thead>
<tr>
<th>Model</th>
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$p < 5e-6$
Contributions


2. Combine evidence from multiple paths between entity pairs.

3. Entity Aware RNN for chains of reasoning
Multiple Paths

Melinda → Bill

spouse

Bill → Microsoft

chairman

Microsoft → Seattle

headquartered
Multiple Paths

Gates Foundation

Melinda (CEO of Microsoft)

Bill (chairman of Microsoft)

Microsoft (located in Seattle)

Spouse of Bill and CEO of the Gates Foundation
Multiple Paths

- Melinda
- Bill
- Gates Foundation
- CEO
- Jane Doe
- John Doe
- Seattle
- spouse
- chairman
- headquartered
- located in
- friend
- married to
- born in
Multiple Paths

- Melinda
  - spouse
  - friend
  - married to Jane Doe
  - born in

- Bill
  - chairman
  - married to John Doe
  - CEO

- Gates Foundation
  - located in

- Microsoft
  - headquartered

- Seattle
Multiple Paths

Melinda → Bill (spouse) → Microsoft (chairman) → Gates Foundation (headquartered in Seattle) → Jane Doe (friend) → married to John Doe (born in Seattle) → RNN encoder
Multiple Paths

- Melinda
  - spouse: Bill
  - friend: Jane Doe
  - married to: John Doe

- Bill
  - chairman: Microsoft
  - located in: Seattle

- Microsoft
  - headquartered: Seattle

- Seattle
  - located in: Seattle

- Gates Foundation
  - CEO: Melinda
  - spouse: Bill
  - born in: Jane Doe
Melinda -> spouse -> Bill

Bill -> chairman -> Microsoft

Microsoft -> headquartered -> Seattle

Melinda -> friend -> Jane Doe

Jane Doe -> married to -> John Doe

John Doe -> born in -> Jane Doe

Gates Foundation

RNN encoder
Multiple Paths

Gates Foundation

Melinda
- spouse
  - Bill
  - chairman
    - Microsoft
      - headquartered
        - Seattle

- CEO
- friend
  - Jane Doe
  - married to
    - John Doe

- born in
- located in
- lives in??

RNN encoder
Multiple Paths

- Melinda
- Bill
- Gates Foundation
  - CEO
  - spouse
  - chairman
- Microsoft
  - headquartered
- Seattle
  - located in
  - similarity metric
    - lives in??
- Jane Doe
  - friend
  - married to
- John Doe
  - born in
  - RNN encoder
Score Pooling

lives in??

similarity metric

Path 1

Path 2

Path 3
Score Pooling

1. Max pool: \[ \max(\alpha_1, \alpha_2, \ldots, \alpha_N) \]

Neelakantan et al’ 15
Score Pooling

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Score Pooling

1. Max pool: \( \max(\alpha_1, \alpha_2, \ldots, \alpha_N) \)

- Path 1
- Path 2
- Path 3

Similarity metric

Neelakantan et al' 15

Neelakantan et al' 15
Score Pooling

1. Max pool: \( \max(\alpha_1, \alpha_2, \ldots, \alpha_N) \)

2. Avg. pool: 
\[
\frac{1}{N} \left( \sum_{i=1}^{N} \alpha_i \right)
\]

Neelakantan et al’ 15
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Score Pooling

Path 1
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Similarity metric

Neelakantan et al’ 15

lives in??
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Neelakantan et al’ 15

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Path 1
Path 2
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Similarity metric

lives in??
Score Pooling

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2. Avg. pool: \[ \frac{1}{N} \left( \sum_{i=1}^{N} \alpha_i \right) \]

3. Top(k): \[ \frac{1}{k} \left( \sum_{i=1}^{k} s_i \right) \]

Neelakantan et al’ 15

Similarity metric: lives in??
Path 1
Path 2
Path 3
Score Pooling

1. Max pool: \( \max(\alpha_1, \alpha_2, \ldots, \alpha_N) \)

2. Avg. pool: 
   \[
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   \]

3. Top(k): 
   \[
   \frac{1}{k} \left( \sum_{i=1}^{k} s_i \right)
   \]

Neelakantan et al’ 15

---

lives in??

similarity metric

Path 1

Path 2

Path 3

Top(2)

0.95

0.96

0.94

0.18
4. LogSumExp: \[ \log\left(\sum_{i=1}^{N} \exp(\alpha_i)\right) \]
Score Pooling

4. LogSumExp: \( \log\left(\sum_{i=1}^{N} \exp(\alpha_i)\right) \)
Score Pooling

4. LogSumExp: \[ \log\left(\sum_{i=1}^{N} \exp(\alpha_i)\right) \]

1.85

0.96 0.94 0.18

LSE

similarity metric

Path 1 Path 2 Path 3

lives in??
Score Pooling

4. LogSumExp: \[ \log\left(\sum_{i=1}^{N} \exp(\alpha_i)\right) \]

\[ \frac{\partial LSE}{\partial \alpha_i} = \frac{\exp(\alpha_i)}{\sum_i \exp(\alpha_i)} \]

Path 1
Path 2
Path 3

Simularity metric
Score Pooling

4. LogSumExp: \[ \log\left(\sum_{i=1}^{N} \exp(\alpha_i)\right) \]

\[ \frac{\partial \text{LSE}}{\partial \alpha_i} = \frac{\exp(\alpha_i)}{\sum_i \exp(\alpha_i)} \]

4. LogSumExp:

\[ \log(\sum_{i=1}^{N} \exp(\alpha_i)) \]

\[ \frac{\partial \text{LSE}}{\partial \alpha_i} = \frac{\exp(\alpha_i)}{\sum_i \exp(\alpha_i)} \]

LSE

Training Loss

Gradient Steps

Path 1

Path 2

Path 3

lives in??

similarity metric
Results
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20
Contributions


2. Combine evidence from multiple paths between entity pairs.

3. Entity Aware RNN for chains of reasoning
JFK located in NY

NYC located in NY
airport_serves_location??

JFK located in NYC located in NY

0.9276

Yankee Stadium located in NYC located in NY
Entity Representation

Melinda spouse Bill chairman Microsoft headquartered Seattle
Entity Representation

Melinda  spouse  Bill  chairman  Microsoft  headquartered  Seattle
Entity Representation

Melinda

Bill

Microsoft

Seattle
Entity Representation

1. Learn separate representation for each entity.

Melinda  Bill  Microsoft  Seattle
Entity Representation

1. Learn separate representation for each entity.
Entity Representation

1. Learn separate representation for each entity.

rare occurrence; hard to learn good representations.
Entity Representation

1. Learn separate representation for each entity.
2. Represent entities by their annotated types.

rare occurrence; hard to learn good representations.
Entity Representation

1. Learn separate representation for each entity.
2. Represent entities by their **annotated types**

Annotated types in KB

- Melinda
- Jane Doe

1. CEO
2. Philanthropist
3. Duke University alumni
4. American Citizen

- Bill
- Microsoft
- Seattle

1. American Citizen
2. Small business owner

rare occurrence; hard to learn good representations.
Entity Representation

$$\text{Melinda} = \text{1. CEO} + \text{2. Philanthropist} + \text{3. Duke University alumni} + \text{4. American Citizen}$$

$$\text{Jane Doe} = \text{1. American Citizen} + \text{2. Small business owner}$$
Entity Representation

Entity is represented as the sum of their annotated types

\[
\text{Melinda} = \text{1. CEO} + \text{2. Philanthropist} + \text{3. Duke University alumni} + \text{4. American Citizen}
\]

\[
\text{Jane Doe} = \text{1. American Citizen} + \text{2. Small business owner}
\]
Entity Aware RNNs for Chains of Reasoning

- Melinda
- spouse
- Bill
- chairman
- Microsoft
- headquartered
- Seattle
- dummy_rel

similarity metric: 0.94

country of HQ?
Results
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<tr>
<td>Single Model</td>
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<td>Single Model + Entity</td>
<td>71.74</td>
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<tr>
<td>Single Model + Types</td>
<td>73.26</td>
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<tr>
<th>Model</th>
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<tbody>
<tr>
<td>Single Model</td>
<td>70.11</td>
</tr>
<tr>
<td>Single Model + Entity</td>
<td>71.74</td>
</tr>
<tr>
<td>Single Model + Types</td>
<td>73.26</td>
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$p < 5e-6$
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Predictive Clauses
Predictive Clauses

/people/person/place_of_birth(A,B) ←→ 'was born in'(A,X) & ‘commonly known as’(X,B)
Predictive Clauses

\[ \text{Freebase} \]
\[ /\text{people/person/place\_of\_birth}(A,B) \quad \iff \quad 'was\ born\ in'(A,X) \ & \ 'commonly\ known\ as'(X,B) \]
Predictive Clauses

\[ /people/person/place_of_birth(A,B) \iff 'was born in'(A,X) \amp 'commonly known as'(X,B) \]

Textual relations
# Predictive Clauses

## Universal Schema

\[
\begin{align*}
\text{Freebase} & \quad \text{Textual relations} \\
/people/person/place_of_birth(A,B) & \quad \text{\textquoteleft was born in\textquoteright}(A,X) & \text{\textquoteleft commonly known as\textquoteright}(X,B)
\end{align*}
\]
Predictive Clauses

\[ /\text{people/person/place_of_birth}(A,B) \leftrightarrow 'was born in'(A,X) \& 'commonly known as'(X,B) \]

Freebase

Textual relations
Predictive Clauses

Frebase

/people/person/place_of_birth(A,B) ↔ 'was born in'(A,X) & 'commonly known as'(X,B)

/book/written_work/original_language(A,B) ↔ /book/written_work_author(A,X) & 'address'(X,Y)

& /people/person/nationality^{-1}(Y,Z) & people/person/languages(Z,B)
Predictive Clauses

Textual relations

\[ /people/person/place_of_birth(A,B) \iff 'was born in'(A,X) \& 'commonly known as'(X,B) \]

\[ /book/written_work/original_language(A,B) \iff /book/written_work_author(A,X) \& 'address'(X,Y) \& /people/person/nationality^{-1}(Y,Z) \& people/person/languages(Z,B) \]
Predictive Clauses

\[ \text{Freebase} \]

\[
\text{/people/person/place_of_birth}(A,B) \quad \leftrightarrow \quad \text{‘was born in’}(A,X) \land \text{‘commonly known as’}(X,B)
\]

\[
\text{/book/written_work/original_language}(A,B) \quad \leftrightarrow \quad \text{/book/written_work_author}(A,X) \land \text{‘address’}(X,Y)
\]

\& \text{/people/person/nationality}^{-1}(Y,Z) \land \text{people/person/languages}(Z,B)

\[
\text{/aviation/airport/serves??}
\]

Sandy_Lake_Airport \quad \dashrightarrow \quad \text{Sandy_Lake_First_Nation}

Entity Aware Model
Predictive Clauses

\[ /people/person/place_of_birth(A,B) \iff 'was born in'(A,X) \& 'commonly known as'(X,B) \]

\[ /book/written_work/original_language(A,B) \iff /book/written_work_author(A,X) \& 'address'(X,Y) \]

\& /people/person/nationality^{-1}(Y,Z) \& people/person/languages(Z,B)

\[ /aviation/airport/serves?? \]

Entity Aware Model

Sandy_Lake_Airport

Sandy_Lake_First_Nation

\[ /location/contains \]

\[ '(in northwestern)'^{-1} \]

Ontario

Sandy_Lake_First_Nation
Predictive Clauses

Textual relations

\( \text{Freebase} \)

\( /\text{people/person/place_of_birth}(A,B) \leftrightarrow 'was born in'(A,X) \& 'commonly known as'(X,B) \)

\( /\text{book/written_work/original_language}(A,B) \leftrightarrow /\text{book/written_work_author}(A,X) \& 'address'(X,Y) \)

\& /people/person/nationality^{-1}(Y,Z) \& people/person/languages(Z,B) \)

\( \rightarrow /\text{aviation/airport/serves??} \)

Entity Aware Model

Sandy_Lake_Airport

Sandy_Lake_First_Nation
Predictive Clauses

[Textual relations]

\[ /\text{people/person/place_of_birth}(A,B) \iff \text{'was born in'}(A,X) \& \text{'commonly known as'}(X,B) \]

\[ /\text{book/written_work/original_language}(A,B) \iff /\text{book/written_work_author}(A,X) \& \text{'address'}(X,Y) \]

\[ \& /\text{people/person/nationality}^{-1}(Y,Z) \& /\text{people/person/languages}(Z,B) \]

[Diagram]

- Sandy_Lake_Airport
- Sandy_Lake_First_Nation
- /location/contains
- Ontario
- Toronto_Royal_Music_Hall
- /aviation/airport/serves??
- Big Trout Lake
- /geography/lake/basin_countries
- Canada
- 'including the'
- Sandy_Lake_First_Nation
- and to
- Sandy_Lake_Airport

[Entity Aware Model]
Conclusion
Conclusion

• Introduced a high-capacity single RNN model for relation extraction
Conclusion

• Introduced a high-capacity single RNN model for relation extraction

• Combines evidences among multiple paths and sources of evidence
Conclusion

- Introduced a high-capacity single RNN model for relation extraction
- Combines evidences among multiple paths and sources of evidence
- Entity Aware!
Conclusion

• Introduced a high-capacity single RNN model for relation extraction

• Combines evidences among multiple paths and sources of evidence

• Entity Aware!

Thanks!