Towards End-to-End Reasoning for Question Answering

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What is reasoning?
Simple Question Answering Model

What is “Hello” in French?

Bonjour.
Examples

• Most neural machine translation systems (Cho et al., 2014; Bahdanau et al., 2014)
  • Need very high hidden state size (~1000)
  • No need to query the database (context) $\rightarrow$ very fast
• Most dependency, constituency parser (Chen et al., 2014; Klein et al., 2003)
• Sentiment classification (Socher et al., 2013)
  • Classifying whether a sentence is positive or negative
• Most neural image classification systems
  • The question is always “What is in the image?”
• Most classification systems
Simple Question Answering Model

Problem: parametric model has finite, pre-defined capacity.

“You can’t even fit a sentence into a single vector!” Dan Roth
What is “Hello” in French?

Bonjour.

<table>
<thead>
<tr>
<th>English</th>
<th>French</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hello</td>
<td>Bonjour</td>
</tr>
<tr>
<td>Thank you</td>
<td>Merci</td>
</tr>
</tbody>
</table>

Context (Knowledge Base)
Examples

• Wiki QA (Yang et al., 2015)
• QA Sent (Wang et al., 2007)
• WebQuestions (Berant et al., 2013)
• WikiAnswer (Wikia)
• Free917 (Cai and Yates, 2013)

• Many deep learning models with external memory (e.g. Memory Networks)
What does a frog eat?

Context (Knowledge Base)

<table>
<thead>
<tr>
<th>Eats</th>
<th>IsA</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Amphibian, insect)</td>
<td>(Frog, amphibian)</td>
</tr>
<tr>
<td>(insect, flower)</td>
<td>(Fly, insect)</td>
</tr>
</tbody>
</table>

Something is missing ...
What does a frog eat?

Fly

<table>
<thead>
<tr>
<th>Eats</th>
<th>IsA</th>
<th>First Order Logic</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Amphibian, insect)</td>
<td>(Frog, amphibian)</td>
<td>IsA(A, B) ^ IsA(C, D) ^ Eats(B, D) \rightarrow Eats(A, C)</td>
</tr>
<tr>
<td>(insect, flower)</td>
<td>(Fly, insect)</td>
<td></td>
</tr>
</tbody>
</table>

Context (Knowledge Base)
Examples

• Semantic parsing
  • GeoQA (Krishnamurthy et al., 2013; Artzi et al., 2015)

• Science questions
  • Aristo Challenge (Clark et al., 2015)
  • ProcessBank (Berant et al., 2014)

• Machine comprehension
  • MCTest (Richardson et al., 2013)
“Vague” line between factoid QA and reasoning QA

• Factoid:
  • The required information is explicit in the context
  • The model often needs to handle lexical / syntactic variations

• Reasoning:
  • The required information may not be explicit in the context
  • Need to combine multiple facts to derive the answer

• There is no clear line between the two!
If our objective is to “answer” difficult questions ...

• We can try to make the machine more capable of reasoning (better model)

OR

• We can try to make more information explicit in the context (more data)
What does a frog eat?

Fly

Eats  IsA  First Order Logic
(Amphibian, insect)  (Frog, amphibian)  IsA(A, B) ^ IsA(C, D) ^ Eats(B, D)  \rightarrow  Eats(A, C)

(insect, flower)  (Fly, insect)

Context (Knowledge Base)

Who makes this? Tell me it’s not me ...
End-to-end QA Model with Reasoning Capability

What does a frog eat?

Frog is an example of amphibian. Flies are one of the most common insects around us. Insects are good sources of protein for amphibians.

Fly

Context in natural language
Is end-to-end always feasible?

• **No.** End-to-end systems perform poorly if either:
  • Data is limited
  • Reasoning is super complicated

• Balance between reasoning capability and end-to-end-ness
In the diagram at the right, circle O has a radius of 5, and CE = 2. Diameter AC is perpendicular to chord BD. What is the length of BD?

a) 2  b) 4  c) 6  
**d) 8**  e) 10
What is the length of BD?

In the diagram at the right, circle O has a radius of 5, and CE = 2. Diameter AC is perpendicular to chord BD.
Method

• Learn to map question to logical form
• Learn to map local context to logical form
  • Text $\rightarrow$ logical form
  • Diagram $\rightarrow$ logical form
• Global context is already formal!
  • Manually defined
  • “If AB = BC, then \( \angle CAB = \angle ACB \)"
• Solver on all logical forms
  • We created a reasonable numerical solver
In triangle ABC, line DE is parallel with line AC, DB equals 4, AD is 8, and DE is 5. Find AC.

(a) 9  (b) 10  (c) 12.5  (d) 15  (e) 17

Difficult to directly map text to a long logical form!
In triangle ABC, line DE is parallel with line AC, DB equals 4, AD is 8, and DE is 5. Find AC.

(a) 9  (b) 10  (c) 12.5  (d) 15  (e) 17
Numerical solver

- Translate literals to numeric equations

<table>
<thead>
<tr>
<th>Literal</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equals(LengthOf(AB),d)</td>
<td>((A_x-B_x)^2+(A_y-B_y)^2-d^2 = 0)</td>
</tr>
<tr>
<td>Parallel(AB, CD)</td>
<td>((A_x-B_x)(C_y-D_y)-(A_y-B_y)(C_x-D_x) = 0)</td>
</tr>
<tr>
<td>PointLiesOnLine(B, AC)</td>
<td>((A_x-B_x)(B_y-C_y)-(A_y-B_y)(B_x-C_x) = 0)</td>
</tr>
<tr>
<td>Perpendicular(AB,CD)</td>
<td>((A_x-B_x)(C_x-D_x)+(A_y-B_y)(C_y-D_y) = 0)</td>
</tr>
</tbody>
</table>

- Find the solution to the equation system
- Use off-the-shelf numerical minimizers (Wales and Doye, 1997; Kraft, 1988)
- Numerical solver can choose not to answer question
Dataset

- **Training questions** (67 questions, 121 sentences)
  - Seo et al., 2014
  - High school geometry questions

- **Test questions** (119 questions, 215 sentences)
  - We collected them
  - SAT (US college entrance exam) geometry questions

- We manually annotated the text parse of all questions
Results (EMNLP 2015)

*** 0.25 penalty for incorrect answer
In the figure to the left, triangle ABC is inscribed in the circle with center O and diameter AC. If AB = AO, what is the degree measure of angle ABO?

(A) 15°  
(B) 30°  
(C) 45°  
(D) 60°  
(E) 90°  

Solve Problem
Limitations

- Dataset is small
- Required level of reasoning is very high
- A lot of manual efforts (annotations, rule definitions, etc.)
- End-to-end system is simply hopeless

- Collect more data?
- Change task?
- Curriculum learning? (Do more hopeful tasks first?)
Diagram QA (2016)

Stanford QA (2016)

bAbI QA (2016)

Geometry QA (2015)
Q: The process of water being heated by sun and becoming gas is called

A: Evaporation
Is DQA subset of VQA?

- Diagrams and real images are very different
- Diagram components are simpler than real images
- Diagram contains a lot of information in a single image
- Diagrams are few (whereas real images are almost infinitely many)
Problem

What comes before second feed?

Difficult to latently learn relationships
Strategy

What does a frog eat?  

Diagram Graph

Fly
Diagram Parsing

[Diagram showing a series of LSTM layers connected with fully connected layers and candidate relationship features.]

[Diagram text includes elements like Add, No change, Fully Connected, Stacked LSTM Network, and Fully Connected with candidate relationships and feature vectors.]
Attention visualization

The diagram depicts The life cycle of

a) frog 0.924
b) bird 0.02
c) insecticide 0.054
d) insect 0.002

How many stages of Growth does the diagram Feature?

a) 4 0.924
b) 2 0.02
c) 3 0.054
d) 1 0.002

What comes before Second feed?

a) digestion 0.0
b) First feed 0.15
c) indigestion 0.0
d) oviposition 0.85
## Results (ECCV 2016)

<table>
<thead>
<tr>
<th>Method</th>
<th>Training data</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random (expected)</td>
<td>-</td>
<td>25.00</td>
</tr>
<tr>
<td>LSTM + CNN</td>
<td>VQA</td>
<td>29.06</td>
</tr>
<tr>
<td>LSTM + CNN</td>
<td>AI2D</td>
<td>32.90</td>
</tr>
<tr>
<td>Ours</td>
<td>AI2D</td>
<td>38.47</td>
</tr>
</tbody>
</table>
Limitations

• You need a lot of prior knowledge to answer some questions!
  • E.g. “Fly is an insect”, “Frog is an amphibian”

• You can’t really call this *reasoning*...
  • Rather matching algorithm
  • No complex inference involved
Geometry QA (2015)

Diagram QA (2016)

Stanford QA (2016)

bAbI QA (2016)
bAbI QA

• Weston et al., 2015 (Facebook)
• Synthetically generated reasoning story-question pairs
• 20 tasks, 1k questions in each task
• Each story can be as long as 200 sentences
• Requires reasoning over multiple sentences
• Should be trained end-to-end (no manual rules or external language resources)
• Passed a task if accuracy >= 95%
Tasks Examples

**Task 3: Three Supporting Facts**
John picked up the apple.
John went to the office.
John went to the kitchen.
John dropped the apple.
Where was the apple before the kitchen? A: office

**Task 7: Counting**
Daniel picked up the football.
Daniel dropped the football.
Daniel got the milk.
Daniel took the apple.
How many objects is Daniel holding? A: two

**Task 13: Compound Coreference**
Daniel and Sandra journeyed to the office.
Then they went to the garden.
Sandra and John travelled to the kitchen.
After that they moved to the hallway.
Where is Daniel? A: garden

**Task 19: Path Finding**
The kitchen is north of the hallway.
The bathroom is west of the bedroom.
The den is east of the hallway.
The office is south of the bedroom.
How do you go from den to kitchen? A: west, north
How do you go from office to bathroom? A: north, west
Previous work

- **RNN**: Tested as baseline by Weston et al. (2015)
  - Performs very poorly; hidden state is inherently unstable for long-term dependency

- **Softmax attention mechanism** (Sukhbaatar et al., 2015, Xiong et al., 2016)
  - Uses shared external memory with softmax attention mechanism
  - Attend on different facts over several layers
  - **DMN**: Combines RNN and attention mechanism

- **Problem**:
  - Vanilla softmax attention cannot distinguish between similar sentences at different time steps.
  - Cannot capture time locality information.
Query-regression networks

• Name comes from “Logic Regression” (not linear regression)
  • Transforming the original query to an easier-to-answer query, in vector space

• Pure RNN-based model
  • completely internal memory
  • Single unit recurring over time and layers (simple)
  • Although RNN, does not suffer from long-term dependency problem
  • Take full advantage of RNN’s capability to model sequential data
  • Can be considered as using “sigmoid attention”
Query-regression networks

\[ h_t = \alpha x_t + \gamma q_t \]

\[ q_t = \beta x_t + \delta q_{t-1} \]

1. Sandra got the apple there.
2. Sandra dropped the apple there.
3. Daniel took the apple there.
4. Sandra went to the hallway.
5. Daniel journeyed to the garden.

Where is Sandra?
Where is Sandra?
Where is Daniel?
Where is Daniel?
Where is Daniel?

\[ \hat{y} = h_5 \]

\[ q = \begin{cases} \text{Where is the apple?} \end{cases} \]
Parallelization

\[
\begin{pmatrix}
    h_1^T \\
    h_2^T \\
    h_3^T \\
    \vdots \\
    h_T^T
\end{pmatrix} = \exp\left\{ \begin{pmatrix}
    0 & -\infty & -\infty & \cdots & -\infty \\
    b_2 & 0 & -\infty & \cdots & -\infty \\
    b_2 + b_3 & b_3 & 0 & \cdots & -\infty \\
    \vdots & \vdots & \vdots & \ddots & \vdots \\
    \sum_{j=2}^T b_j & \sum_{j=3}^T b_j & \sum_{j=4}^T b_j & \cdots & 0
\end{pmatrix}\right\} \begin{pmatrix}
    z_1 h_1^T \\
    z_2 h_2^T \\
    z_3 h_3^T \\
    \vdots \\
    z_T h_T^T
\end{pmatrix}
\]

\[
H = [L \circ \exp (L [B \circ L'])] [Z \circ \tilde{H}]
\]
## Results on bAbI QA 1k

<table>
<thead>
<tr>
<th>Model</th>
<th># of Tasks Passed</th>
<th>Average Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSTM (Weston et al., 2015)</td>
<td>0</td>
<td>48.7</td>
</tr>
<tr>
<td>End-to-end Memory Networks (Sukhbaatar et al., 2015)</td>
<td>10</td>
<td>84.8</td>
</tr>
<tr>
<td>QRN (2 layers)</td>
<td>13</td>
<td>90.1</td>
</tr>
<tr>
<td>QRN (3 layers)</td>
<td><strong>15</strong></td>
<td>88.7</td>
</tr>
</tbody>
</table>
# Qualitative Results of QRN

## Task 2: Two Supporting Facts

<table>
<thead>
<tr>
<th>Event</th>
<th>Layer 1</th>
<th>Layer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandra picked up the apple there.</td>
<td>0.95</td>
<td>0.89</td>
</tr>
<tr>
<td>Sandra dropped the apple.</td>
<td>0.83</td>
<td>0.05</td>
</tr>
<tr>
<td>Daniel grabbed the apple there.</td>
<td>0.88</td>
<td>0.93</td>
</tr>
<tr>
<td>Sandra travelled to the bathroom.</td>
<td>0.01</td>
<td>0.18</td>
</tr>
<tr>
<td>Daniel went to the hallway.</td>
<td>0.01</td>
<td>0.24</td>
</tr>
</tbody>
</table>

**Where is the apple?**

- hallway (hallway)

## Task 3: Three Supporting Facts

<table>
<thead>
<tr>
<th>Event</th>
<th>Layer 1</th>
<th>Layer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mary got the football there.</td>
<td>0.82</td>
<td>1.00</td>
</tr>
<tr>
<td>John went back to the bedroom.</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>Mary journeyed to the office.</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>Mary journeyed to the bathroom.</td>
<td>0.44</td>
<td>0.00</td>
</tr>
<tr>
<td>Mary dropped the football.</td>
<td>0.62</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**Where was the football before the bathroom?**

- office (office)

## Task 7: Counting

<table>
<thead>
<tr>
<th>Event</th>
<th>Layer 1</th>
<th>Layer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mary journeyed to the garden.</td>
<td>0.67</td>
<td>0.08</td>
</tr>
<tr>
<td>Mary journeyed to the office.</td>
<td>0.91</td>
<td>0.44</td>
</tr>
<tr>
<td>Sandra grabbed the apple there.</td>
<td>0.02</td>
<td>0.34</td>
</tr>
<tr>
<td>Sandra discarded the apple.</td>
<td>0.26</td>
<td>0.61</td>
</tr>
<tr>
<td>Daniel went to the bedroom.</td>
<td>0.70</td>
<td>0.44</td>
</tr>
</tbody>
</table>

**How many objects is Sandra carrying?**

- none (none)

## Task 15: Deduction

<table>
<thead>
<tr>
<th>Event</th>
<th>Layer 1</th>
<th>Layer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mice are afraid of wolves.</td>
<td>0.11</td>
<td>0.99</td>
</tr>
<tr>
<td>Gertrude is a mouse.</td>
<td>0.77</td>
<td>0.99</td>
</tr>
<tr>
<td>Cats are afraid of sheep.</td>
<td>0.01</td>
<td>0.99</td>
</tr>
<tr>
<td>Winona is a mouse.</td>
<td>0.14</td>
<td>0.85</td>
</tr>
<tr>
<td>Sheep are afraid of wolves.</td>
<td>0.02</td>
<td>0.98</td>
</tr>
</tbody>
</table>

**What is Gertrude afraid of?**

- wolf (wolf)
## Results on bAbI QA 10k*

<table>
<thead>
<tr>
<th>Method</th>
<th># of Tasks Passed</th>
<th>Average Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>End-to-end Memory Networks (Sukhbaatar et al., 2015)</td>
<td>17</td>
<td>95.8</td>
</tr>
<tr>
<td>Dynamic Memory Networks Improved (Xiong et al., 2016)</td>
<td>19</td>
<td>97.2</td>
</tr>
<tr>
<td>QRN (2 layers)</td>
<td>18</td>
<td>96.8</td>
</tr>
</tbody>
</table>
Limitations

• Okay, the reasoning process is interesting ...

• But “this is a fake dataset”! (by anonymous reviewers)
SQuAD (Stanford QA)

Immune_system
The Stanford Question Answering Dataset

- Recently released: June 2016
- 100k+ paragraph-question-answer triples
- Paragraphs from most popular articles in Wikipedia
- Answer is the subphrase of the paragraph
Stanford QA vs Other “Big” QA Datasets

• CNN / Daily Mail (Hermann et al., 2015)
  • Google DeepMind
  • Document-Summary pairs from web
  • Cloze test on summary (fill in the blank)

• Children’s Book Test (Hill et al., 2015)
  • Facebook AI Research
  • Project Gutenberg: Children’s books
  • Cloze test on 21st sentence

• Take away: Cloze test, and crawled data
• Stanford QA is direct question, and carefully controlled (turked)
Model: Co-Attention

**Barak Obama** is the president of the U.S.

Who leads the United States?

\[
i_s = 0 \quad i_f = 1
\]
Embedding Module

- Word embedding is fragile against unseen words
- Char embedding can’t easily learn semantics of words
- Use both!

- Char embedding as proposed by Yoon (2015)
Attention Mechanism: Motivation

While Seattle’s weather is very nice in summer, its weather is very rainy in winter, making it one of the most gloomy cities in the U.S.

Q: Which city is gloomy in winter?
Attention Mechanism

• **Theoretically**, RNN can propagate information over a long distance through its recurrent state

• **Practically**, this is very difficult
  • Inherently unstable state, even using LSTM (Weston et al., 2014)
  • State size is fixed (Bahdanau et al., 2014)

• Attention provides *shortcut access* to distant information

• **Co-Attention**: question attends on context, and context attends on question. Similar in spirit to, but fundamentally different from, Lu et al. (2016).
Results: Metric

- Each question is answered by 2-5 different people (by indicating the answer phrase in the paragraph)
- **Exact Match**: the answer exactly matches one of the answers
- **F1 Score**: geometric average of precision and recall

- “The actors were paid $1.5 million on average.”

- **Q**: Who were paid more than $1 million on average?
## Results on Test (Sept. 29, 2016)

<table>
<thead>
<tr>
<th>Model</th>
<th>Exact Match (%)</th>
<th>F1 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (Stanford)</td>
<td>40.4</td>
<td>51.0</td>
</tr>
<tr>
<td>Match LSTM v1 (Singapore)</td>
<td>54.5</td>
<td>67.7</td>
</tr>
<tr>
<td>Match LSTM v2 (Singapore)</td>
<td>60.5</td>
<td>70.7</td>
</tr>
<tr>
<td>Dynamic Chunk Reader (IBM)</td>
<td><strong>62.5</strong></td>
<td>71.0</td>
</tr>
<tr>
<td>Co-Attention (Ours)</td>
<td>61.8</td>
<td><strong>72.5</strong></td>
</tr>
</tbody>
</table>
### Attention Visualization

<table>
<thead>
<tr>
<th>56e0bb9f7aa994140058e5cf</th>
<th>Other than his scientific achievements, what was Tesla famous for?</th>
</tr>
</thead>
<tbody>
<tr>
<td>showmanship</td>
<td>showmanship</td>
</tr>
<tr>
<td>showmanship</td>
<td>showmanship</td>
</tr>
<tr>
<td>showmanship</td>
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<td>showmanship</td>
<td>showmanship</td>
</tr>
<tr>
<td>showmanship</td>
<td>showmanship</td>
</tr>
<tr>
<td>0.637</td>
<td></td>
</tr>
<tr>
<td>0.555</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>56e0ef0c7231d4119001ac376</th>
<th>What were Tesla’s sisters’ names?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milka, Angelina and Marica</td>
<td>Milka, Angelina and Marica</td>
</tr>
<tr>
<td>Milka, Angelina and Marica</td>
<td>Milka, Angelina and Marica</td>
</tr>
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</tr>
<tr>
<td>Milka, Angelina and Marica</td>
<td>Milka, Angelina and Marica</td>
</tr>
<tr>
<td>0.555</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>56e0ef0c7231d4119001ac376</th>
<th>In 1861, Tesla attended the Lower or Primary School in Smiljan, where he completed Lower Real School.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.555</td>
<td></td>
</tr>
</tbody>
</table>
Reasoning Level

Geometry QA (2015)

How about here?

Stanford QA (2016)

Diagram QA (2016)

bAbI QA (2016)

End-to-end-ness
Important questions

- Is fully end-to-end reasoning system feasible with reasonable amount of data? → Probably no

- How to balance between:
  - data size
  - model priors (manually defined rules, annotations, etc.)

- How to naturally incorporate model priors (which might be structured data) into the model?
Thank you!

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- http://seominjoon.github.io