Task-Oriented Query Reformulation with Reinforcement Learning

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Motivation

Query: “uiuc natural language processing class”

Search Engine

CS546 Machine Learning in NLP (Spring 2018)
https://courses.engr.illinois.edu/cs546/ 
Prerequisites are a basic understanding of NLP, probability, statistics, linear algebra and machine 
learning, as well as solid programming skills. Students will learn to read the current literature, and apply 
these models to NLP problems. They will be required to do a research project, to give class 
presentations, and to write ... 
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CS 447: Natural Language Processing 
https://courses.engr.illinois.edu/cs447/fa2015/index.html 
Topics: This course provides an introduction to computational linguistics, from morphology (word 
formation) and syntax (sentence structure) to semantics (meaning), and natural language processing 
applications such as parsing, machine translation, generation and dialog systems. Objectives: At the 
end of this course, ... 
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NLP @ Illinois 
nlp.cs.illinois.edu/ 
Dec 21, 2010 - Home; Research; Faculty; Seminars; Courses; Software, Tools, and Data; Contact Us 
... Our research spans many areas of computational linguistics and natural language engineering, 
including speech recognition and synthesis, language modeling, ... We run a mailing list as well as a 
weekly NLP lunch.
Motivation

Query: “uiuc class ai language words computer science”

Search Engine

Course Descriptions | CS @ ILLINOIS - Computer Science at the ... [Link]
May 28, 2013 - CS 421 - Progmg Languages & Compilers ... Progmg Languages & Compilers, B3, 31375, LCD, 3, 1700 - 1815, T R , 1320 Digital Computer Lab, A Mattix Beckman, Jr. Progmg ...
Program translation: be able to write a syntax-directed translator from abstract syntax to intermediate representations (a). ()

Programming Languages, Formal Methods, and ... - CS @ Illinois [Link]
word cloud with programming-related words The growing complexity and scale of software poses formidable challenges for reliability, security, performance, and productivity. Our faculty tackle these problems by developing innovative techniques in programming language design and semantics; techniques and tools for ...

Artificial Intelligence | CS @ ILLINOIS - Computer Science at the ... [Link]
Natural language processing systems understand written and spoken language, possibilities include automatic translation of text from one language to another ... Cram's Chicago Business – Based on the deep computer science talent pool produced by the University of Illinois and other area schools, ServiceNow plans hire ...
Motivation

Using **inexact** or **long** queries in search engines tend to result in poor document retrieval

- Vocabulary Mismatch Problem
- Iterative Searching
Idea: Automatic Query Reformulation

Query: “uiuc class ai language words computer science”

Search Engine

Reformulator

Query: “uiuc natural language processing class”

Course Descriptions | CS @ ILLINOIS - Computer Science at the ... https://cs.illinois.edu/courses/prof/C5421
May 28, 2013 - CS 421 - Programming Languages & Compilers ... Programming Languages & Compilers, 135, 307-17, 12:30-1:30 PM T R., 3310 Digital Computer Lab. A Mattx Beckman Jr. Programming ... Program translation: be able to write a syntax-directed translator from abstract syntax to intermediate representations a. (1)

Programming Languages, Formal Methods, and ... CS @ Illinois https://cs.illinois.edu/programming-languages-formal-methods-and-software-engineering/wordcloud with programming-related words: The growing complexity and scale of software poses formidable challenges for reliability, security, performance, and productivity. Our faculty tackle these problems by developing innovative techniques in programming language design and semantics: techniques and tools for...

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Model as a Reinforcement Learning Problem

- Hard to create annotated data for queries
  - What is the “correct” query?
  - Successful queries are not unique
- Learn directly from reward based on relevant document retrieval
- Train to use search engine as a black box
Automatic Query Reformulation

Original Query $q_0$ → Reformulator $q_t$ → Search Engine $D_t$ → Documents $D_t$ → Scorer $D^*$ → Relevant Documents

Reward $D_t$
Reinforcement Learning: Policy Algorithms

- Directly learn policy of how to act
- Policy ($\pi$) gives probabilities of taking an action ($a$) in a given state ($s$) using parameters theta ($\theta$)
  $$\pi_{\theta}(a,s) = P(a \mid s, \theta)$$
- Find policy that maximizes reward by finding the best parameters $\theta$
- Learn policy instead of a value function
  - Q-learning learns a value function
Policy Gradient Algorithms

- $J(\theta) = \text{Expected reward for policy } \pi_\theta \text{ with parameters } \theta$
- **Goal**: Maximize $J(\theta)$
- **Update policy parameters $\theta$ using gradient ascent**
  - Follow gradient with respect to $\theta$ ($\nabla_\theta$):
    \[
    \theta := \theta + \alpha \nabla_\theta J(\theta)\]

**REINFORCE**
- Monte Carlo Policy Gradient
  \[
  \theta_{t+1} = \theta_t + \alpha r_t \nabla_\theta \log(\pi_\theta(a_t|s_t))
  \]
Policy Gradient Algorithms

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- REINFORCE
  - Monte Carlo Policy Gradient
    $$\theta_{t+1} = \theta_t + \alpha r_t \nabla_\theta \log(\pi_\theta(a_t|s_t))$$
    Reward at step $t$
REINFORCE with Baseline

- Monte Carlo Policy gradient algorithms suffer from high variance
  - Problem: If $r_t$ is always positive, probabilities of actions just keep going up
- Rather than update when a reward is positive or negative, update when a reward is better or worse than expected
- Baseline:
  - Value to subtract from the reward to reduce variance
  - Estimate the reward $v_t$ for state $s_t$ using a value function

$$\theta_t = \theta_t + \alpha (r_t - v_t) \nabla_{\theta} \log(\pi_{\theta}(a_t|s_t))$$
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$$
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$$

(Reward - Baseline)
Reformulator: Inputs and Outputs

● Inputs:
  ○ Original query: \( q_0 = (w_1, \ldots, w_n) \)
  ○ Documents from \( q_0 \): \( D_0 \)
  ○ Candidate term: \( t_i \)
  ○ Context terms: \( (t_{i-k}, \ldots, t_{i+k}) \)
    ■ Terms around candidate term to give information on how word is used

● Outputs:
  ○ Probability of using candidate term in new query (Policy): \( P(t_i \mid q_0) \)
  ○ Estimated Reward Value (Baseline): \( \hat{R} \)
REINFORCE

- Stochastic Objective Function for Policy

\[ C_a = (R - \bar{R}) \sum_{t \in T} - \log P(t|q_0), \]

- Value Network Trained to Minimize:

\[ C_b = \alpha \| R - \bar{R} \|^2, \]

- Minimize using stochastic gradient descent
Reward

R = Recall@K

\[ R@K = \frac{|D_K \cap D^*|}{|D^*|} \]

Where \( D_K \) are the top-K retrieved documents and \( D^* \) are the relevant documents.

\( R@40 \) used for training reinforcement learning models.
Reformulator: Model

Use Word2vec to convert Inputs terms to vector representations
Reformulator: Model

- Use CNN/RNN to create fixed length output
- Use CNN/RNN to create fixed length vector outputs
Reformulator: Model

$P(t_i | q_0)$

$\bar{R}$

- Use CNN followed by Max Pool or RNN to create fixed length output
- Concatenate outputs from original query and candidate terms
- Generate policy and reward outputs

Concatenate outputs from original query and candidate terms
Reformulator: Model

\[ P(t_i | q_0) = \sigma(U^T \tanh(W(\phi_a(v) || \phi_b(e_i)) + b)) \]

\[ \bar{R} = \sigma(S^T \tanh(V(\phi_a(v) || \bar{e}) + b)) \]
Reinforcement Learning Extensions

- **Sequential model of term addition**
  - Produces shorter queries

- **Oracle to estimate upper bound on performance for RL methods**
  - Split *validation or test* data into N smaller subsets
  - Train an RL agent on each subset until it overfits the subset
  - Average the rewards achieved by each agent on their given subset
Baseline Method: Supervised Learning

- Assume terms independently affect query results
- Train binary classifier to predict if adding a term to a given query will increase recall
- Add terms that are predicted to increase performance above a threshold
Experiments: Datasets

- **TREC - Complex Answer Retrieval (TREC-CAR)**
  - Query: wikipedia title and subsection title
  - Relevant Documents: Paragraphs in subsection

- **Jeopardy**
  - Query: A Jeopardy question
  - Relevant Documents: Wikipedia article with title of the answer

- **Microsoft Academic (MSA)**
  - Query: Paper Title
  - Relevant Documents: Papers cited in the original paper

| Dataset     | Corpus                | Docs | Train | Valid | Test  | Relevant Docs/Query | Words/Doc |
|-------------|-----------------------|------|-------|-------|-------|--------------------|-----------|
| TREC-CAR    | Wikipedia Paragraphs  | 3.5M | 585k  | 195k  | 195k  | 3.6  | 5.7 | 84 | 68 |
| Jeopardy    | Wikipedia Articles    | 5.9M | 118k  | 10k   | 10k   | 1.0  | 0.0 | 462 | 990 |
| MSA         | Academic Papers       | 480k | 270k  | 20k   | 20k   | 17.9 | 21.5 | 165 | 158 |
| (Original) Daikon Cultivation | “...many types of pickles are made with daikon, includ...”
  | “Certain varieties of daikon can be grown as a winter...”
  | “In Chinese cuisine, turnip cake and chai tow kway...” |
|-----------------------------|--------------------------------------------------|
| (Reformulated) Daikon Cultivation root seed grow fast-growing Chinese leaves | “...many types of pickles are made with daikon, includ...”
  | “Certain varieties of daikon can be grown as a winter...”
  | “The Chinese and Indian varieties tolerate higher....” |
## Results

| Method       | TREC-CAR | Jeopardy | MSA |
|--------------|----------|----------|-----|
|              | R@40     | P@10     | MAP@40 | R@40     | P@10     | MAP@40 | R@40 | P@10 | MAP@40 |
| Raw-Lucene   | 43.6     | 7.24     | 19.6   | 23.4     | 1.47     | 7.40   | 12.9  | 7.24 | 3.36   |
| Raw-Google   | -        | -        | -      | 30.1     | 1.92     | 7.71   | -    | -    | -      |
| PRF-TFIDF    | 44.3     | 7.31     | 19.9   | 29.9     | 1.91     | 7.65   | 13.2  | 7.27 | 3.50   |
| PRF-RM       | 45.1     | 7.35     | 19.5   | 30.5     | 1.96     | 7.64   | 12.3  | 7.22 | 3.38   |
| PRF-Emb      | 44.5     | 7.32     | 19.0   | 30.1     | 1.92     | 7.74   | 12.2  | 7.22 | 3.20   |
| Vocab-Emb    | 44.2     | 7.30     | 19.1   | 29.4     | 1.87     | 7.80   | 12.0  | 7.21 | 3.21   |
| SL-FF        | 44.1     | 7.29     | 19.7   | 30.8     | 1.95     | 7.70   | 13.2  | 7.28 | 3.88   |
| SL-CNN       | 45.3     | 7.35     | 19.8   | 31.1     | 1.98     | 7.79   | 14.0  | 7.42 | 3.99   |
| SL-Oracle    | 50.8     | 8.25     | 21.0   | 38.8     | 2.50     | 9.92   | 17.3  | 10.12| 4.89   |
| RL-FF        | 44.1     | 7.29     | 20.0   | 31.0     | 1.98     | 7.81   | 13.9  | 7.33 | 3.81   |
| RL-CNN       | 47.3     | 7.45     | 20.3   | 33.4     | 2.14     | 8.02   | 14.9  | 7.63 | 4.30   |
| RL-RNN       | **47.9** | **7.52** | **20.6** | **33.7** | **2.12** | **8.07** | **15.1** | **7.68** | **4.35** |
| RL-RNN-SEQ   | 47.4     | 7.48     | 20.3   | 33.4     | 2.13     | 8.01   | 14.8  | 7.63 | 4.27   |
| RL-Oracle    | 55.9     | 9.06     | 23.0   | 42.4     | 2.74     | 10.3   | 24.6  | 12.83| 6.33   |

Table 2: Results on Test sets. We use R@40 as a reward to the RL-based models.
Conclusions

- **RL methods work the best overall**
  - RL-RNN achieves highest scores
  - RL-RNN-SEQ produces shorter queries and is faster
- **There is a large gap between best RL method and RL-Oracle.**
  - Shows there is significant room for improvement using RL methods
Questions?
References

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- Ronald J Williams. 1992. Simple statistical gradient-following algorithms for connectionist reinforcement learning. Machine learning
- Sutton, R. S., & Barto, A. G. (2018). Reinforcement learning: An introduction. Cambridge, MA: MIT Press.
- Query Reformulator Github: https://github.com/nyu-dl/QueryReformulator
- Slides on paper by authors: https://github.com/nyu-dl/QueryReformulator/blob/master/Slides.pdf