UNIVERSITÀ DEGLI STUDI DI PADOVA

QUARTZ

Quantum Information Access and Retrieval Theory

# **Interpretable** Neural network driven by quantum probability theory

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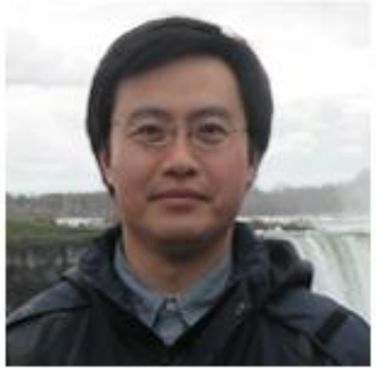
# Done with the collaboration



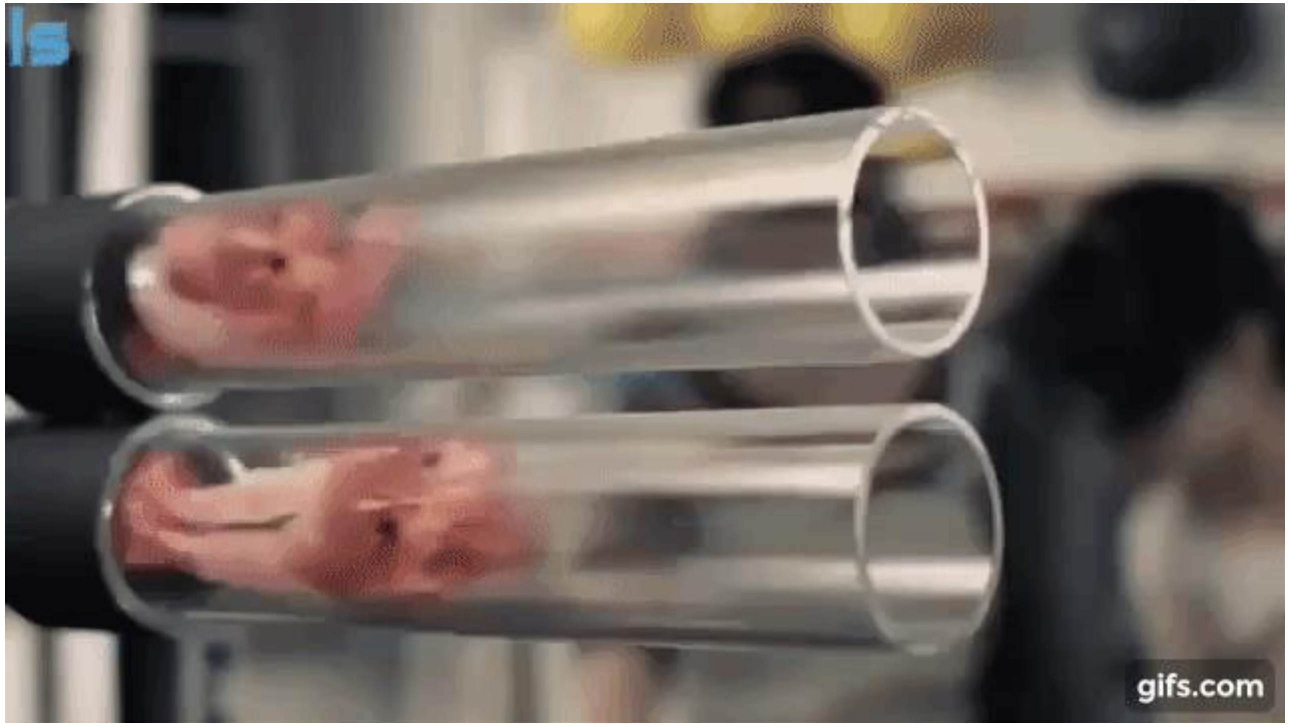


# Contents

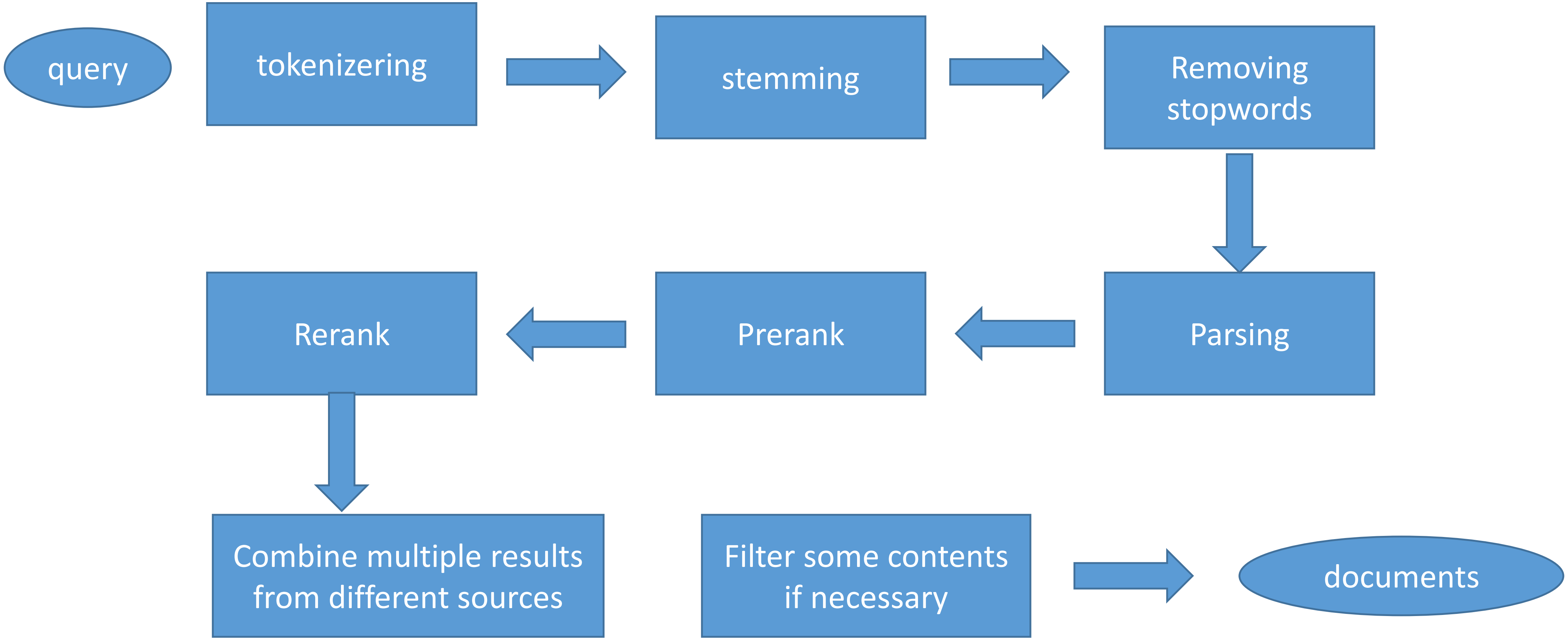
- Motivation: Interpretability in end2end network
- Method: Hilbert Semantic Space
- Applications: language representation and matching
  - Text classification
  - Matching with question answering

# End-to-end Paradigm




https://www.youtube.com/watch?v=TYpBJ71VW9g

# An **Pipeline** example for text processing



# End to end mechanism

- ✓ Less accumulating error
- ✓ Less involvement  with Human beings
- ✓ Improve performance with shared features of the downstream tasks and upstream tasks

- ❖ Hard to adjust
- ❖ Hard to  transfer
- ❖ Hard to understand

We need End to End mechanism, but in a fine-grained way

# What is **Interpretability**

- Post-hoc explanations
  - Take a **learned model** and draw some kind of useful insights
  - E.g. Visualization in machine translation [Liu Yang &Maosong Sun ACL 2017]

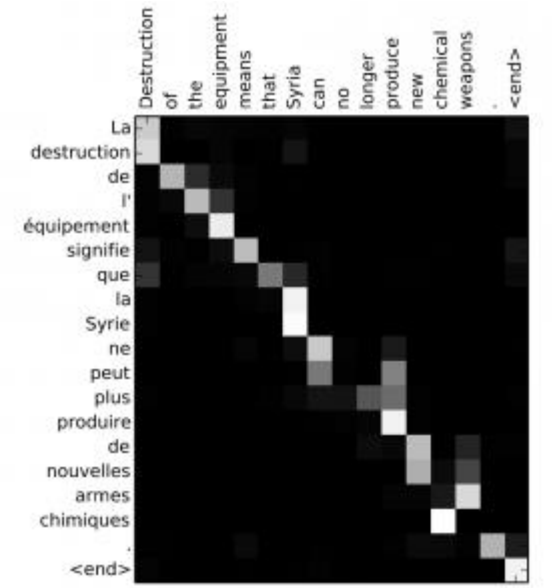
- Transparency
  - Targeting ``how does the model work?'' and seeks to provide some way to understand the core mechanisms
  - E.g. Capsule Network [Hinton NIPS 2017]

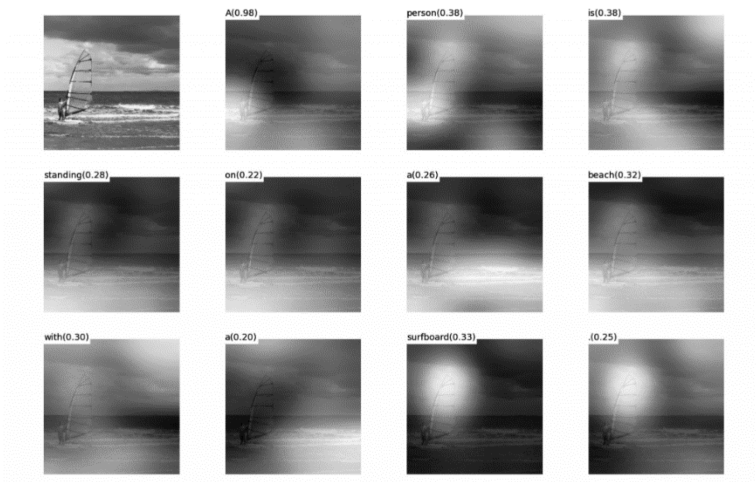
Zachary C Lipton. The mythos of model interpretability. arXiv preprint arXiv:1606.03490, 2016， **ICML** Workshop on Human Interpretability in Machine Learning
Yanzhuo Ding, Yang Liu, Huanbo Luan, and Maosong Sun. Visualizing and understanding neural machine translation. **ACL**, volume 1, pages 1150–1159, 2017.
Sabour S, Frosst N, Hinton G E. Dynamic routing between capsules[C]//**NIPS . 2017**: 3856-3866.

# Interpretability: **Attention**

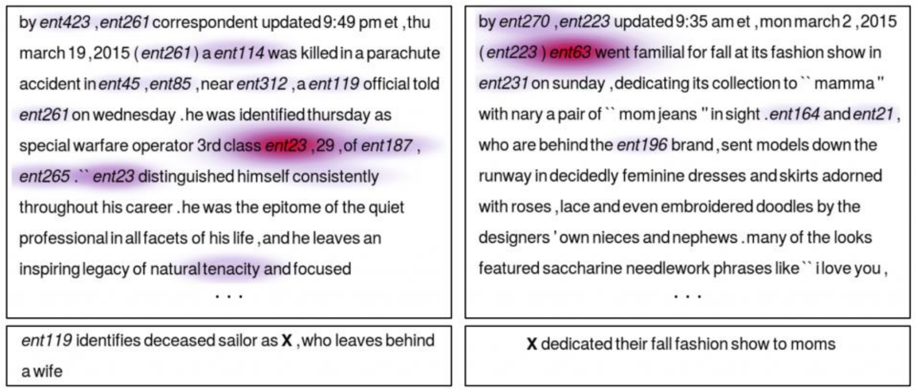
For a given vector $\vec{w}$, we normalize it with **softmax** thus guarantee their sum equals to 0

$$\vec{w}' = softmax(\vec{w}),\ \ w_i = \frac{e^{w_i}}{\sum e^{w_i}}$$




(b) A person is standing on a beach with a surfboard.



# Design each subcomponents in the End-2-end architecture with a good background of the task

- *Both language understanding and artificial intelligence require being able to understand bigger things from knowing about smaller parts*

Christopher Manning 2017

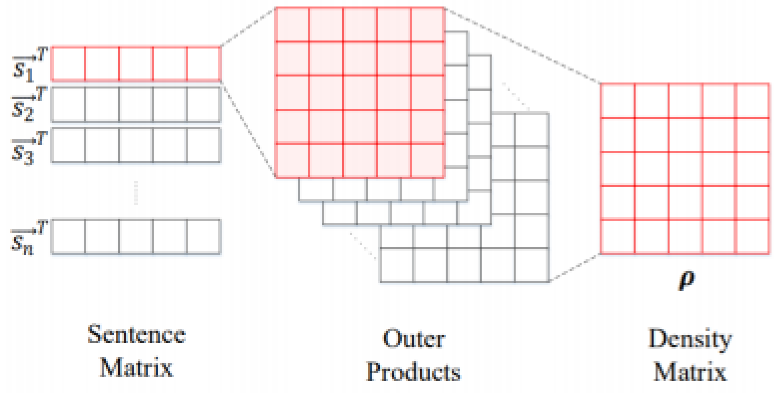
# Motivations

- Design self-***explainable*** subcomponents in end2end network
- Provides more **transparency** as well as **Post-hoc explanations**
- **Theoretically-sound** network

# Related works

- End to End language model for QA **[AAAI 2018]**
- Quantum Many body function for language model in QA **[CIKM 2018]**
- Quantum-inspired word Embedding [ACL REP4NLP 2018]
- **Hilbert Semantic Space** [In process without peer review]
  - Text Representation
  - Text Matching

# End-2-end Language model for QA




Matching with two matrices

- $tr(\rho_1 \rho_2)$
- CNN over $\rho_1 \rho_2$

Zhang Peng, Niu Jiabing, Su Zhan, **Wang Benyou** et al. [End-to-End Quantum-like Language Models with Application to Question Answering] **AAAI 2018**

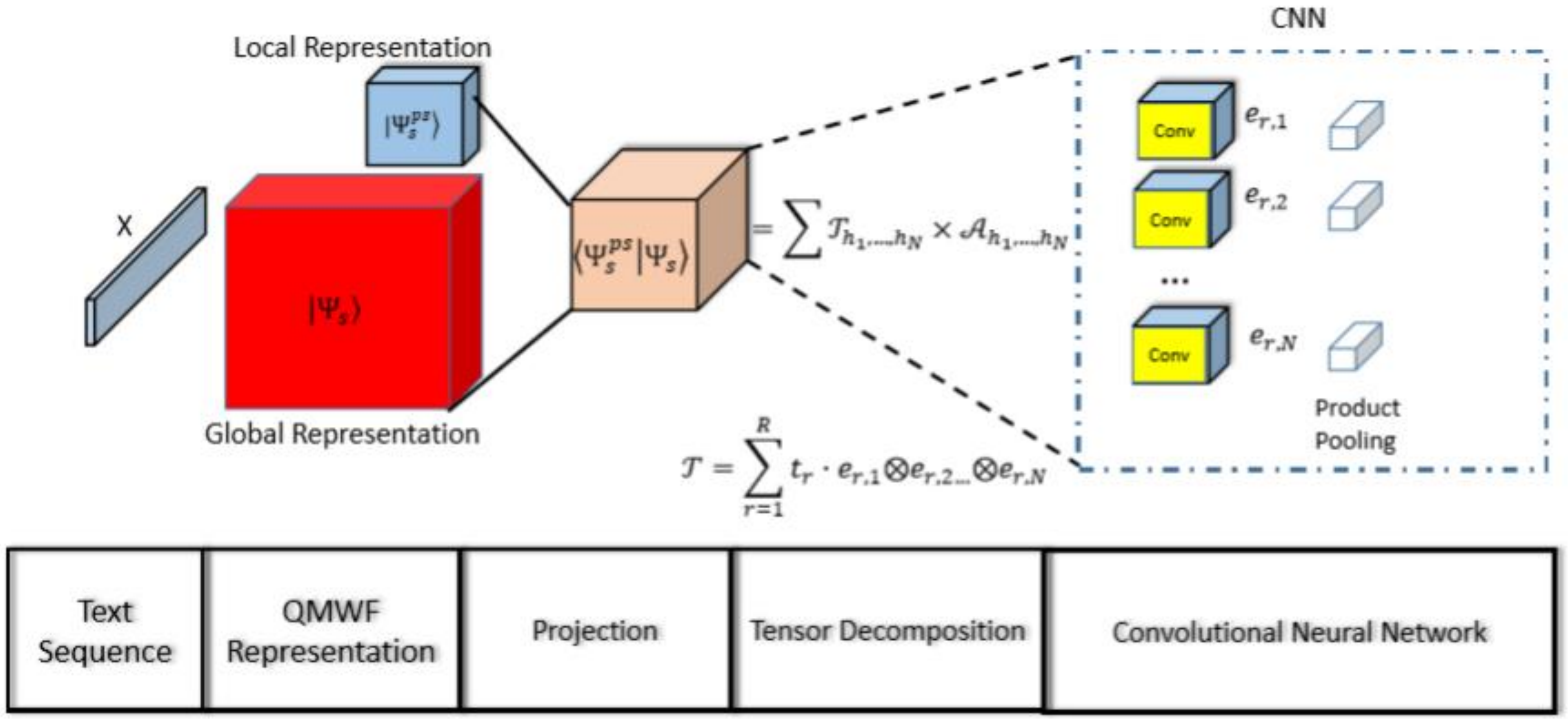
# Metric/similarity for $\rho_q \rho_a$ [e.g. $\mathbf{tr}(\boldsymbol{\rho_q \rho_a})$ or $\boldsymbol{f}_{\mathbf{cnn}}(\boldsymbol{\rho_q \rho_a})$]

- Not theoretically-sound
  - $tr(\rho_q \rho_a)$ can not obtain the maximum value if $\rho_q \neq \rho_a$
  - Can not guarantee $tr(\rho_q \rho_x)$ + $tr(\rho_x \rho_a)$ > $tr(\rho_q \rho_a)$

- Ignoring the mathematical property of density matrix (probability distribution)

- Others
  - Real-valued based instead of **complex-valued**
  - Can not guarantee the unity length of density matrix.

# Quantum many-body function for LM




Use CNN to ***approximate*** Tensor Decomposition in the projection of Quantum Many-Body Language Function

Peng Zhang, Zhan Su, Lipeng Zhang, **Benyou Wang** , Dawei Song. 2018. A Quantum Many-body Wave Function Inspired Language Modeling Approach, **CIKM 2018**

# Complex word-embedding

- superposition with phase

$$z^* = z_1 + z_2 = r_1 e^{i\theta_1} + r_2 e^{i\theta_2}$$
$$= \sqrt{r_1^2 + r_2^2 + 2r_1 r_2 \cos(\theta_2 - \theta_1)} \times e^{i \arctan\left(\frac{r_1 \sin(\theta_1) + r_2 \sin(\theta_2)}{r_1 \cos(\theta_1) + r_2 \cos(\theta_2)}\right)}$$

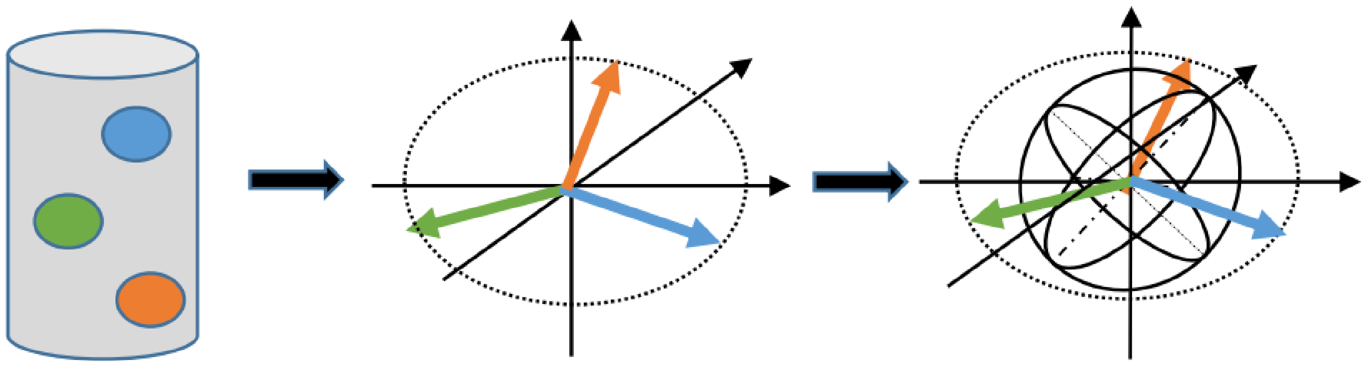
Li Qiuchi, Uprety Sagar, **Wang Benyou** , Song Dawei [Quantum-inspired Complex Word Embedding, ACL 2018 3rd Workshop on Representation Learning for NLP](), **ACL 2018 RepL4NLP**

# Hilbert Semantic Space

- **Unify** these four things in a complex-valued space
  - Sememes
  - Word
  - Phrase/Sentence/Documents
  - Topic as measurements

# Definition

- Sememes as basic state
  - $\{|e_1\rangle, |e_2\rangle, \ldots, |e_n\rangle\}$
- Word as superstition state
  - $|w\rangle = \sum \alpha_i |e_i\rangle$
- Sentence as mixed system



Semantic Hilbert Space

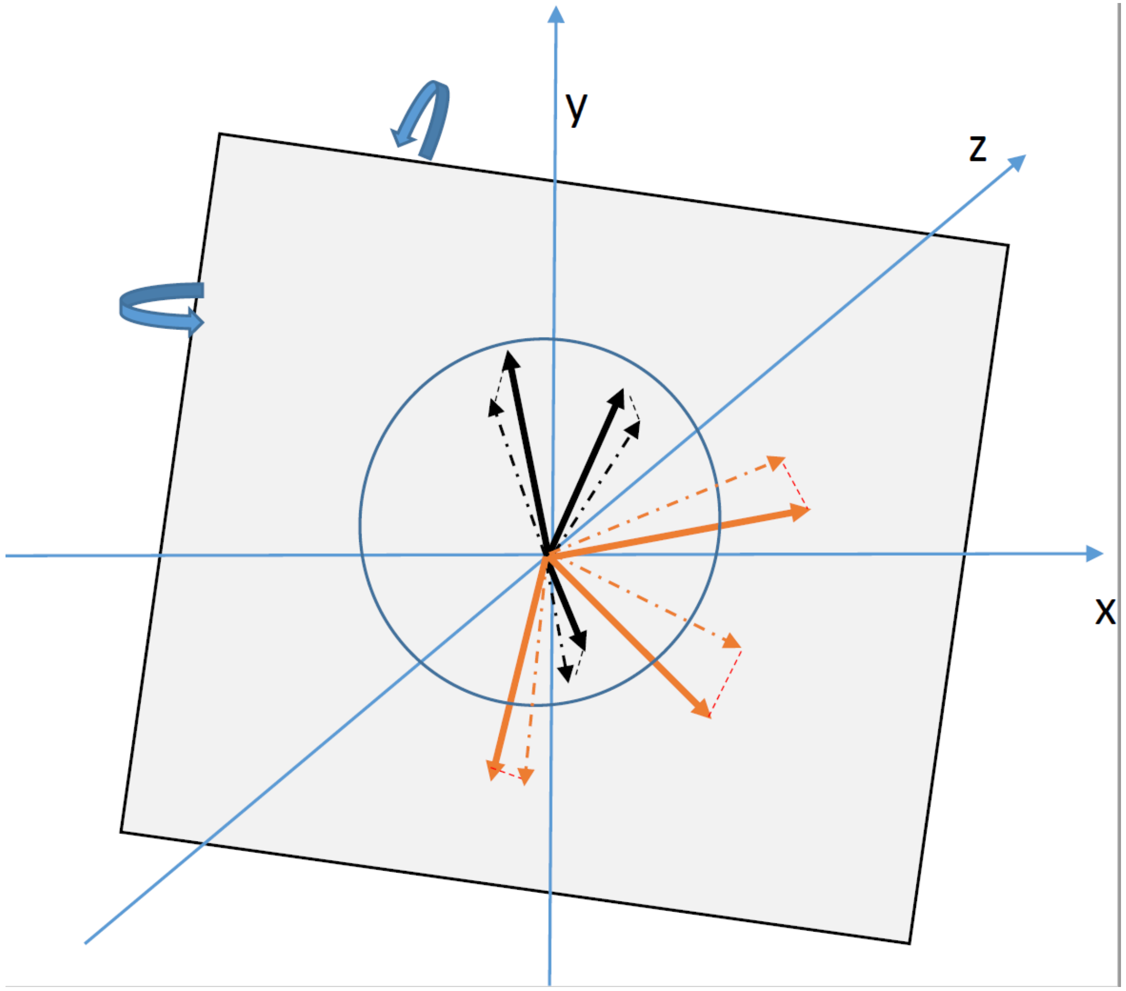
Mixed System

# Complex word embedding

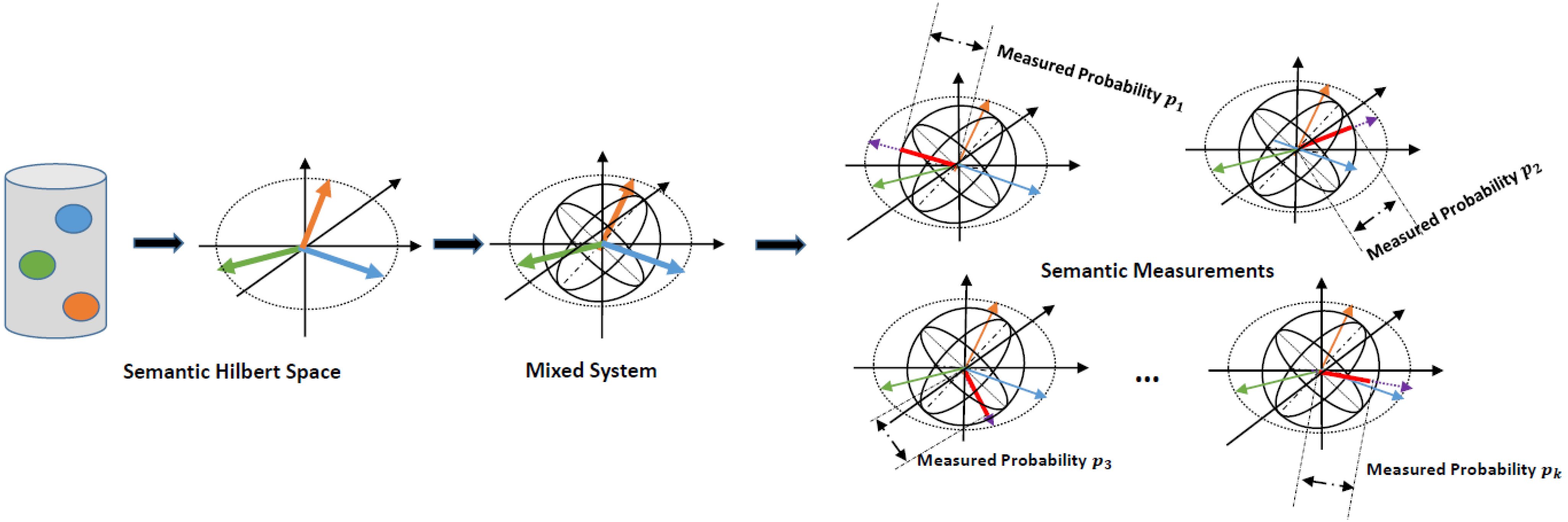
- Dimension: the number of
- Length : weight
- Amplitude part: meaning
- Phase part: polarity ?

- How to infer the overall polarity from the polarity of each words?
  - Is there any quantum phenomena here ?

# Trainable Measurements for sentence classification

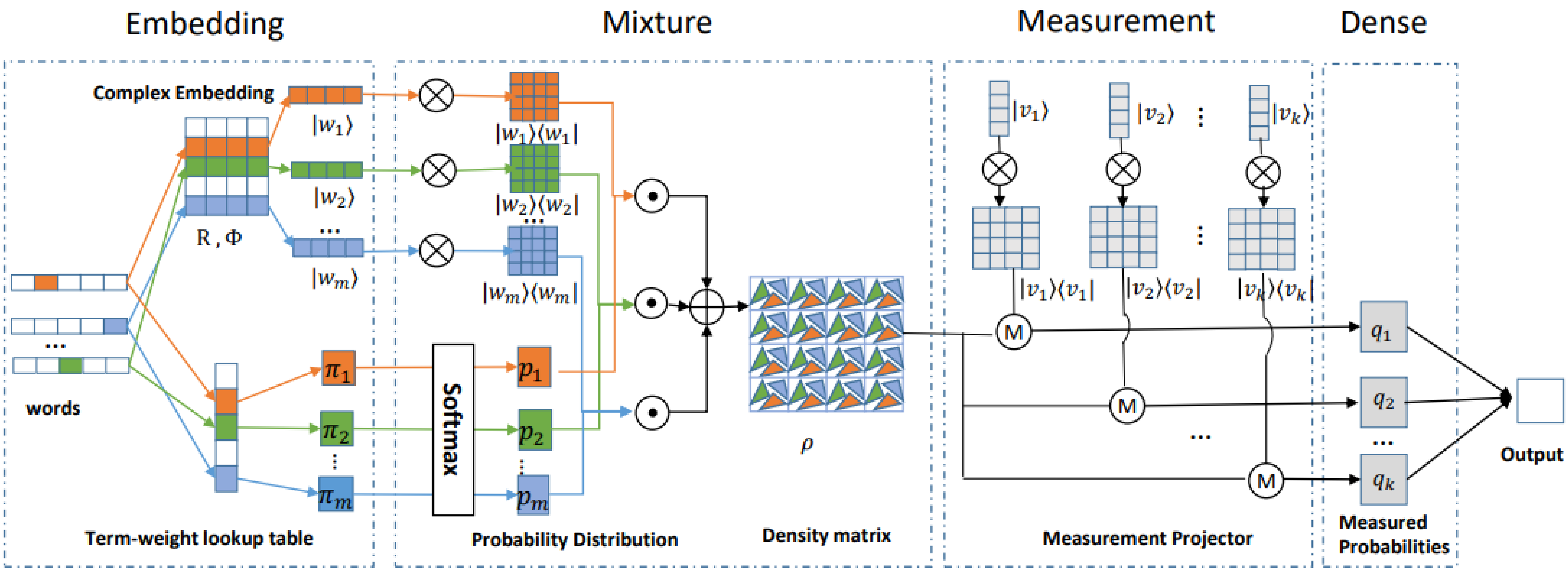


# Framework



Semantic Hilbert Space
Mixed System
Measured Probability $p_1$
Measured Probability $p_2$
Semantic Measurements
Measured Probability $p_3$
...
Measured Probability $p_k$

# Implements




https://github.com/wabyking/qnn.git

# Physical meaning for our models

**Table 3: Physical meaning and constraint for each component**

| Components | Traditional DNN | NNQLM [56] | QPDN |
|---|---|---|---|
| Input embedding | arbitrary real vector $(-\infty, \infty)$ | arbitrary real vector $(-\infty, \infty)$ | unit complex vector, corresponding to superposition state $\{w \mid w \in C^n, \|\|w\|\|_2 = 1\}$ |
| Low-level representation | arbitrary real vector $(-\infty, \infty)$ | fake, real-valued density matrix $\{\rho \mid \rho \in \mathcal{R}^{n*n}\}$, | density matrix, corresponding to mixed state $\{\rho \mid \rho = \rho^*, tr(\rho) = 1, \mu\rho\mu^T > 0\ \forall \mu \neq \overrightarrow{0}, \rho \in C^{n*n}\}$, |
| Abstraction | CNN/RNN/Attention $(-\infty, \infty)$ | CNN $(-\infty, \infty)$ | measurement vector, corresponding to measurement $\{w \mid w \in C^n, \|\|w\|\|_2 = 1\}$ |
| High-level representation | arbitrary real vector $(-\infty, \infty)$ | arbitrary real vector $(-\infty, \infty)$ | real-valued probability, corresponding to measurement result $(0, 1)$ |

# Experiments

**Table 2: Experiment Results in percentage(%). The best performed value (except for CNN/LSTM) for each dataset is in bold.**

| Model | CR | MPQA | MR | SST | SUBJ | TREC |
|---|---|---|---|---|---|---|
| Uni-TFIDF | 79.2 | 82.4 | 73.7 | - | 90.3 | 85.0 |
| Word2vec | 79.8 | **88.3** | 77.7 | 79.7 | 90.9 | 83.6 |
| FastText [28] | 78.9 | 87.4 | 76.5 | 78.8 | 91.6 | 81.8 |
| Sent2Vec [42] | 79.1 | 87.2 | 76.3 | 80.2 | 91.2 | 85.8 |
| CaptionRep [21] | 69.3 | 70.8 | 61.9 | - | 77.4 | 72.2 |
| DictRep [22] | 78.7 | 87.2 | 76.7 | - | 90.7 | 81.0 |
| Ours: QPDN | **81.0** | 87.0 | **80.1** | **83.9** | **92.7** | **88.2** |
| CNN [29] | 81.5 | 89.4 | 81.1 | 88.1 | 93.6 | 92.4 |
| BiLSTM [16] | 81.3 | 88.7 | 77.5 | 80.7 | 89.6 | 85.2 |

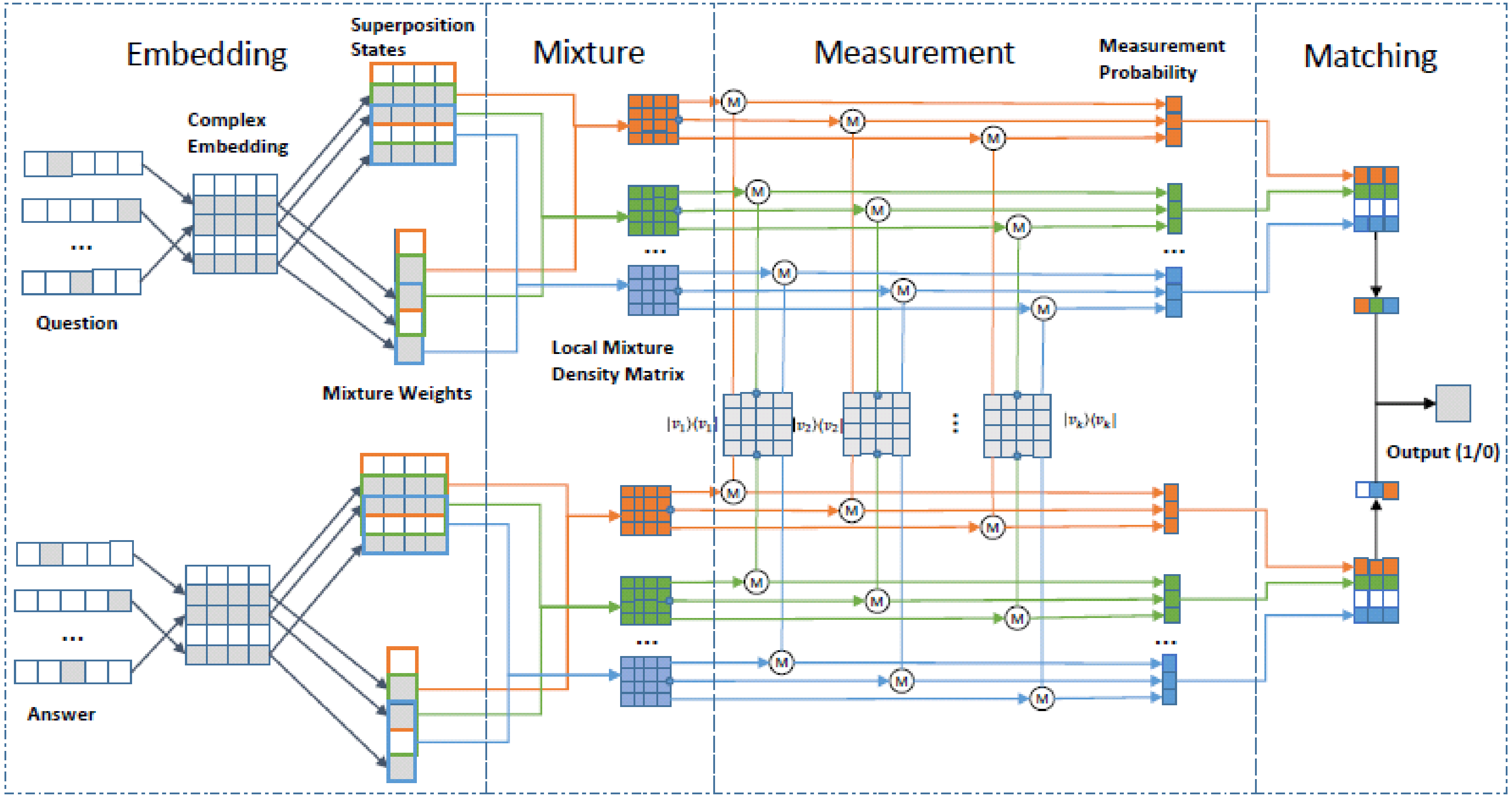
# Case study for our measurement

**Table 7: The learned measurement for dataset MR. They are selected according to nearest words for a measurement vector in Semantic Hibert Space**

| Measurement | Selected neighborhood words |
|---|---|
| 1 | change, months, upscale, recently, aftermath |
| 2 | compelled, promised, conspire, convince, trusting |
| 3 | goo, vez, errol, esperanza, ana |
| 4 | ice, heal, blessedly, sustains, make |
| 5 | continue, warned, preposterousness, adding, falseness |

# Implements for matching

Figure 1: Architecture of Complex-valued Network for Matching. Ⓜ means a measurement operation according to Eq. 2.




https://github.com/wabyking/qnn.git

# Case study

Table 7: The matching patterns for specific sentence pairs in TREC QA. The darker the color, the bigger weight the word is. The [ and ] denotes the possible border of the current sliding windows.

| Question | Correct Answer |
|---|---|
| Who is the [ president or chief executive of Amtrak ] ? | " Long-term success ... " said George Warrington , [ Amtrak 's president and chief executive ] ." |
| When [ was Florence Nightingale born ] ? | ,"On May 12 , 1820 , the founder of modern nursing , [ Florence Nightingale , was born ] in Florence , Italy ." |
| When [ was the IFC established ] ? | [ IFC was established in ] 1956 as a member of the World Bank Group . |
| [ how did women 's role change during the war ] | ..., the [ World Wars started a new era for women 's ] opportunities to .... |
| [ Why did the Heaven 's Gate members commit suicide ] ?, | This is not just a case of [ members of the Heaven 's Gate cult committing suicide ] to ... |

# Experiments

Table 3: Experiment Results on TREC QA Dataset. The best performed values are in bold.

| Model | MAP | MRR |
|---|---|---|
| Bigram-CNN | 0.5476 | 0.6437 |
| LSTM-3L-BM25 | 0.7134 | 0.7913 |
| LSTM-CNN-attn | 0.7279 | 0.8322 |
| aNMM | 0.7495 | 0.8109 |
| MP-CNN | 0.7770 | 0.8360 |
| CNTN | 0.7278 | 0.7831 |
| PWIM | 0.7588 | 0.8219 |
| QLM | 0.6780 | 0.7260 |
| NNQLM-I | 0.6791 | 0.7529 |
| NNQLM-II | 0.7589 | 0.8254 |
| CNM | **0.7701** | **0.8591** |
| Over NNQLM-II | 1.48% ↑ | 4.08% ↑ |

Table 4: Experiment Results on Yahoo QA Dataset. The best performed values are in bold.

| Model | P@1 | MRR |
|---|---|---|
| Okapi BM-25 | 0.2250 | 0.4927 |
| LSTM | 0.4875 | 0.6829 |
| CNN | 0.4125 | 0.6323 |
| CNTN | 0.4654 | 0.6687 |
| QLM | 0.3950 | 0.6040 |
| NNQLM-I | 0.4290 | 0.6340 |
| NNQLM-II | 0.4660 | 0.6730 |
| CNM | **0.4880** | **0.6845** |
| Over NNQLM-II | 4.72% ↑ | 1.45% ↑ |

Table 5: Experiment Results on WikiQA Dataset.The best performed values for each dataset are in bold.

| Model | MAP | MRR |
|---|---|---|
| Bigram-CNN | 0.6190 | 0.6281 |
| BILSTM | 0.6557 | 0.6695 |
| LSTM-attn | 0.6639 | **0.6828** |
| CNN | **0.6701** | 0.6822 |
| QLM | 0.5120 | 0.5150 |
| NNQLM-I | 0.5462 | 0.5574 |
| NNQLM-II | 0.6496 | 0.6594 |
| CNM | 0.6548 | 0.6664 |
| Over NNQLM-II | 1.01% ↑ | 1.01% ↑ |

# Weights

Table 6: Selected learned important words in TREC QA. All words are lower.

| | Selected words |
|---|---|
| Important | studio, president, women, philosophy<br>scandinavian, washingtonian, berliner, championship<br>defiance, reporting, adjusted, jarred |
| Unimportant | 71.2, 5.5, 4m, 296036, 3.5<br>may, be, all, born<br>movements, economists, revenues, computers |

# Learned measurements

Table 8: Selected learned measurements for TREC QA. They were selected according to nearest words for a measurement vector in Semantic Hilbert Space. All the words are lower.

| | Selected neighborhood words for a measurement vector |
|---|---|
| 1 | andes, nagoya, inter-american, low-caste, kazakhstan |
| 2 | cools, injection, boiling,adrift |
| 3 | andrews, paul, manson, bair |
| 4 | historically, 19th-century, genetic, hatchback, shipbuilding |
| 5 | missile, exile, rebellion, darkness |

# Ablation Test

Table 9: Ablation Test. The values in parenthesis are the performance difference between the model and CNM.

| Setting | MAP | MRR |
|---|---|---|
| FastText-MaxPool | 0.6659 (0.1042↓) | 0.7152 (0.1439↓) |
| CNM-Real | 0.7112 (0.0589↓) | 0.7922 (0.0659↓) |
| CNM-Global-Mixture | 0.6968 (0.0733↓) | 0.7829 (0.0762↓) |
| CNM-trace-inner-product | 0.6952 (0.0749↓) | 0.7688 (0.0903↓) |
| CNM | 0.7701 | 0.8591 |

# Conclusion

- More concrete physical meaning
- Self-explainable subcomponents
- More constrain for the subcomponents
- Guided by Quantum probability theory

# Future works

- Current extension:
  - Incorporating more knowledge (e.g. word Polarity)  in phase part
  - Multi-task setting to transfer learned measurement to similar tasks
- New insights
  - Explore high-dimension **tensor network** with Quantum representation
  - **Capsule** Network with Quantum insights
- New tasks:
  - Exploring **generating  language** model with unitary transform
  - Quantum-inspired toy model for **reading comprehension**
  - Exploring position-aware quantum representation for **image**
  - Using complex-valued features **for multimodal dataset**
- New phenomenon:
  - Word **entanglement** for generating a better embedding
  - Cross-language entanglement
- Others:
  - Extending our code to some open-source project
  - Reconsidering embedding and supervised learning for IR