Quantum Mechanics meet Information Search and Retrieval – The QUARTZ Project

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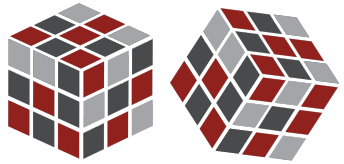
Massimo Melucci, Emanuele Di Buccio, Haiming Liu, Ingo Frommholz

Text Analytic Meetup, Signal AI London, 12/02/2020



QUARTZ

Quantum Information Access and Retrieval Theory

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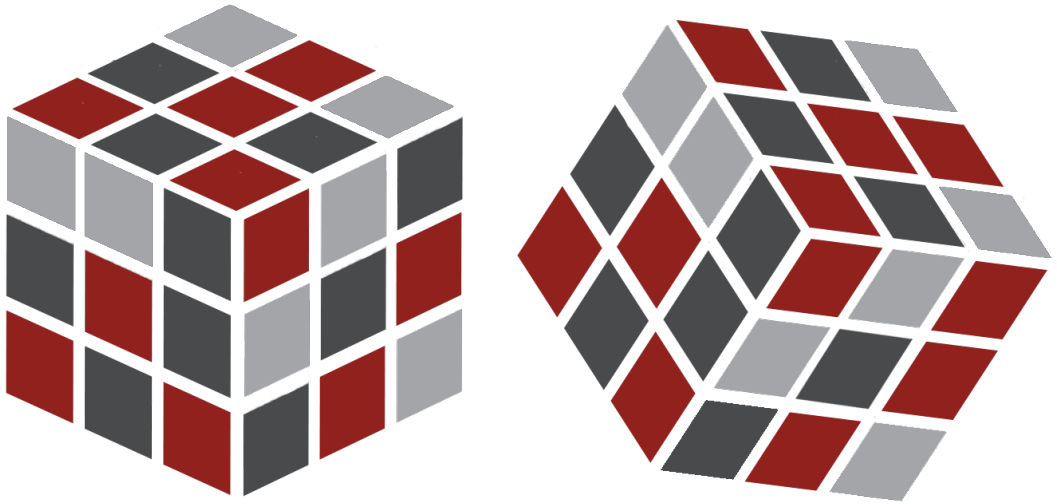
QUARTZ
Quantum Information Access and Retrieval Theory



QUARTZ

Quantum Information Access and Retrieval Theory

- MSCA-ITN-ETN - EU H2020 Marie Curie European Training Network (~3m EUR)
- 13 Early Stage Researchers (ESRs; PhD students)
- Funded 48 months (started January 2017)
- http://www.quartz-itn.eu/

QUARTZ Consortium & Partners

- **Consortium Members**
  University of Padua, Italy
  Open University, UK
  University of Bedfordshire, UK
  Vrije Universiteit Brussel, Belgium
  University of Copenhagen, Denmark
  Brandenburg University of Technology, Germany
  Linnæus University, Sweden
- **Partners**
  Websays SL, Spain
  Signal AI, London, UK
  Queensland University of Technology, Australia
  Staatsbibliothek zu Berlin-Preußischer Kulturbesitz, Germany

QUARTZ Early Stage Researchers (ESRs)

ESR-1

Qiuchi Li

University of Padova, Italy

Querying and Ranking Multimodal Data Using Vector Spaces

ESR-2

Benyou Wang

University of Padova, Italy

Dynamic Content Monitoring and Exploration using Vector Spaces

ESR-3

Amit Kumar Jaiswal

University of Bedfordshire, United Kingdom

A Quantum Model for Interactive Search and Retrieval based on Information Foraging Theory

ESR-7

Dimitris Gkoumas

The Open University, United Kingdom

Multimodal Deep Learning of Abstract Vector Spaces and Adaptive Ranking Scheme

ESR-8

Lucas Lima

University of Copenhagen, Denmark

Characterising Uncertainty in Feature Extraction for Document Ranking

ESR-9

Dongsheng Wang

University of Copenhagen, Denmark

Non-Decomposable Semantic Indicators

ESR-13

Lester Beltran

Vrije Universiteit Brussel, Belgium

Quantum Statistical Distributions for Abstract Conceptual Data

ESR-5

Yousef Younes

Brandenburg University of Technology Cottbus-Senftenberg, Germany

Reasoning in Quantum Logic

ESR-6

Sagar Uprety

The Open University, United Kingdom

Modelling User's Cognitive Dynamics in IAR via Quantum Probability

ESR-10

Aleksandr Lebedev

Linnæus University, Sweden

Quantum open systems and adaptive ranking of information items

ESR-11

Prayag Tiwari

University of Padova, Italy

Decision Theory Based on Contextual Quantum Probability

ESR-12

Suzette Geriente

Vrije Universiteit Brussel, Belgium

Entanglement of Semantic Entities in the Web

Nobody understands Quantum Mechanics!

https://www.youtube.com/watch?v=w3ZRLllWgHI&feature=emb_logo

ESR Presentations

QUARTZ Young Radicals Group (YRG)

Quantum–inspired User Modelling in Information Interaction

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Quantum-inspiration for User Modelling

- Experiments in cognitive science, behavioural economics, etc. show that human decision-making violates fundamental probabilistic and logical axioms.
- Especially in case of contextual decision-making under subjective uncertainty or ambiguity.
  - E.g. Order effects, Conjunction fallacy, Prisoner's dilemma, Preference reversal.
- Current probabilistic models unable to model such behaviour.
- **Quantum Cognition** – Developing user models using the mathematics of Quantum Theory.
  - Successful in modelling "irrational behaviour" and some cognitive biases.
- **My research – Create new user models in information interaction using Quantum Cognition.**

Implications – Predicting cognitive biases

- Decisions, including opinions, are context-dependent, thus subject to manipulation.
  - E.g. - The order in which news documents are shown to users can influence their opinion formation about the events/personalities. (Order effect/bias)
  - Order of negative/positive product reviews can influence consumer decision.
- **Quantum models can predict such cognitive biases in decision-making**.
- **Potential applications**:
  - Detect manipulation of users based on exploitation of cognitive biases. (Goes deeper than fake news/misinformation)
  - Nudge users to improve their decision-making by positively exploiting the biases.

Dynamic Content Monitoring and Exploration using Vector Spaces

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Dynamic content monitoring and exploration using vector spaces

Vector Space

e.g. word embedding (especially complex-valued [1,2]);
semantic Hilbert space (with Quantum probability theory) [3];
tensor space.

[1] **Wang B**., Zhao D., Lioma C., Li Q., Zhang P. and SimonsenJ.G., 2019. Encoding word order in complex embeddings. accepted as ICLR 2020 Spotlight paper

[2] Li Q., **Wang B.** And Melucci M. CNM: An Interpretable Complex-valued Network for Matching. NAACL 2019 Best explainable paper.

[3] **Wang B.**, Li Q., Melucci M. And Song D. Semantic Hilbert Space for Text Representation Learning. WWW 2019.

Potential

Academia

- ✓ Modelling dynamics with well-defined vector space
- ✓ Understanding SOTA models with novel and mathematically-sound angels
- ✓ Investigating Quantum formalisation in representing natural language

industria

- ✓ Better-performed models in textual representation/time-series prediction/event detection/conversation system inspired by Quantum theory
- ✓ Compressing models by means of tensor decompositions &tensor networks
- ✓ Investigating wave-based learning algorithms that can be potentially deployed in wave-based computing hardwares like photons (faster and energy-cheap) [1,2]

[1] Lin, Xing, et al. "All-optical machine learning using diffractive deep neural networks." Science 361.6406 (2018): 1004-1008.

[2] Hughes, Tyler W., et al. "Wave physics as an analog recurrent neural network." Science Advances 5.12 (2019):.

Non-Decomposable Semantic Indicators

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Non-Decomposable Semantic Indicators

- Main task
  - Characterize documents into decomposable and non-decomposable semantic indicators
  - Formalize and integrate them into existing ranking models

- Expected output
  - A mathematical framework for switching between
    - Linguistically naïve <-> Linguistically robust representations of documents
  - A formal modeling
    - Integrating this representation into existing ranking models

Application in Industry and Academia

- Potential application in industry
  - Ranking models
    - Improve the query representation with non-compositional multi-word expression
      - e.g. hot dog (not a dog)
  - Improved representation for NLP tasks
    - Fact checking
    - Question answering over knowledge graph
    - etc.
- Impact on academia
  - Formal research on compositional or non-compositional phrases
  - Bridge the gap between linguistic natural language and knowledge representation

Quantum Open Systems and Adaptive Ranking of Information Items

Aleksandr Lebedev, Linnæus University, Sweden
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My Project

- Is is possible to use
  - quantum probability theory, in particular the theory of open quantum systems
  - in the field of information retrieval, in particular, in adaptive ranking of information items?
- Use this theory to explain so-called **order effects**
  - statistical probability to receive certain answers is influenced by the order in which questions were asked

Relevance

- We will be able to consider a new class of models, quantum probabilistic models
- These models may appear to be more accurate on certain datasets.
- The problem with cognition models is that they are constructed a posteriori, after the experiment was made and, as it seems, have no predictive power.

Characterising Uncertainty in Feature Extraction for Document Ranking

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H2020-MSCA-ITN Grant Agreement N. 721321

PERSONAL INFO

- **Lucas Chaves**
- 26 years old
- Brazilian

CONTACT

EDUCATION

- PhD at University of Copenhagen

- MSc at Federal University of Minas Gerais

RESEARCH

What is my research about?

How could it potentially be applied

PRACTICAL

- MultiFC Dataset for Fact Checking

THEORETICAL

- Multiple Aspects Evaluation Measures
  - relevance, credibility, usefulness, etc.

Quantum-inspired Video Emotion Recognition

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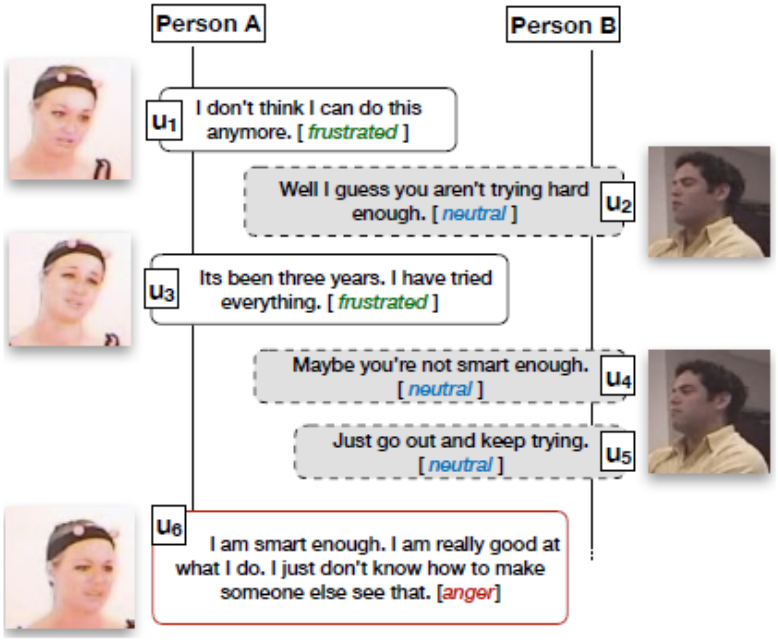
Video Emotion Recognition

Video emotion recognition is a challenging and major research topic.

Challenges:

- An ideal human-machine conversation system should understand human language being inherently multimodal.
- Enabling machines to understand emotions in human conversations mainly relies on the context, e.g., proceeding utterances.

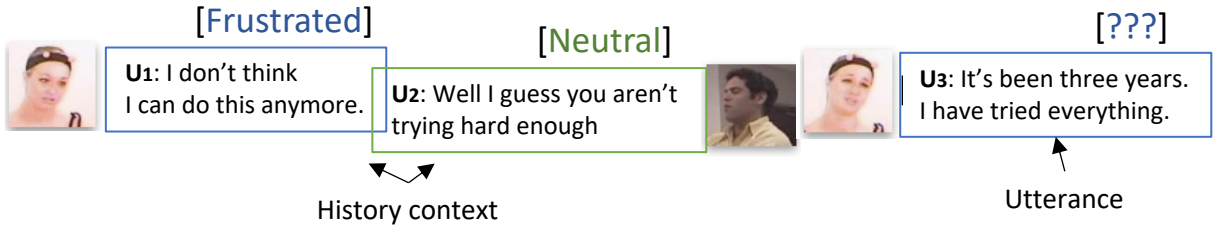


Applications:

- Online human-machine dialogue systems in education, health, etc.
- Opinion mining over chat history and social media trends on YouTube etc.
- Affective dialogue systems where agents understand users' emotions and sentiment to generate emotionally coherent and empathetic responses.
- Other applications such as intelligent systems, e.g., smart homes, counseling, financial forecasting etc.

The ESR7 Project

Text. Visual, and Acoustic Content



Multimodal Representation Learning

Quantum-inspired sentiment embeddings → Quantum cognition for modelling social interactions

Output

Emotion of utterances in conversation videos

- This project first investigates how concepts from quantum mechanisms can help better model interactions across and within different modalities, that is, text, visual, and acoustic content.
- It further investigates how internal-psychological phenomena and social interactions, through a discourse of a dialogue, can be successfully modelled by those concepts, so-called quantum cognition.

A Quantum Model for Interactive Search and Retrieval based on Information Foraging Theory

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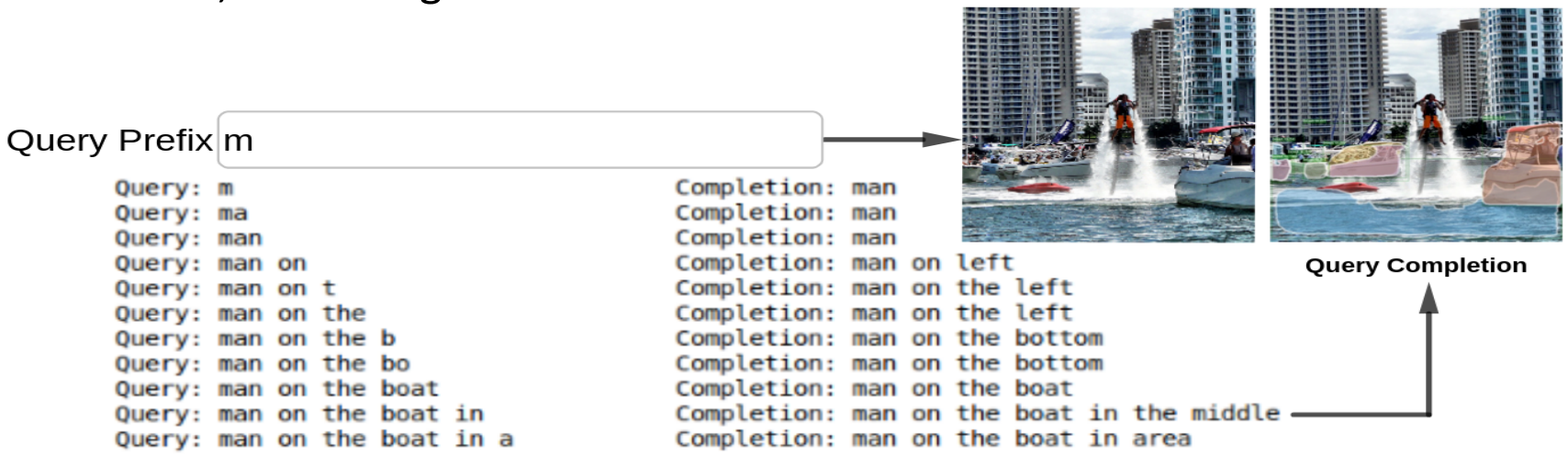
What's the Research about?

A **quantum-inspired framework** for **interactive search** (text-/image-/multimedia search) that model a **user's INs in a Hilbert space** based on **Information Foraging Theory** (IFT)

- Keyword based queries are short/ambiguous/broad and lack cognitive aspects of users, whereas queries in image search explicit the user and tend to be even shorter
- User's having under-specified IN face difficult to textually describe what it is they are seeking
- Model user's actions, interaction (or dynamics) and tactics for satisfying an information need

Research Impact

- Extending quantum-inspired frameworks to quantum-behavioural frameworks using IFT models (patch/scent/diet) for the interpretation of user behaviour.
- Adopting image query auto-completion to SERP presentation can potentially help stakeholders working on visual search, news search, E-commerce, E-retailing etc.



- Cognitive-driven user interaction frameworks can help users in making informed decision.
- Multimedia Recommendation data can be improvised or enriched using IFT models.

Querying and Ranking Multimodal Data Using Vector Spaces

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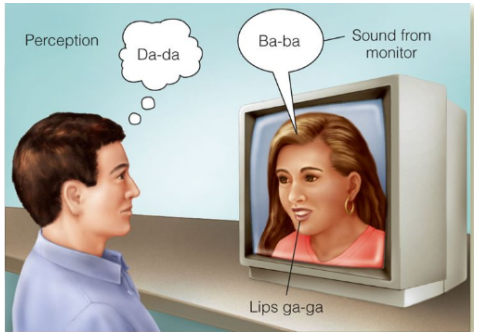
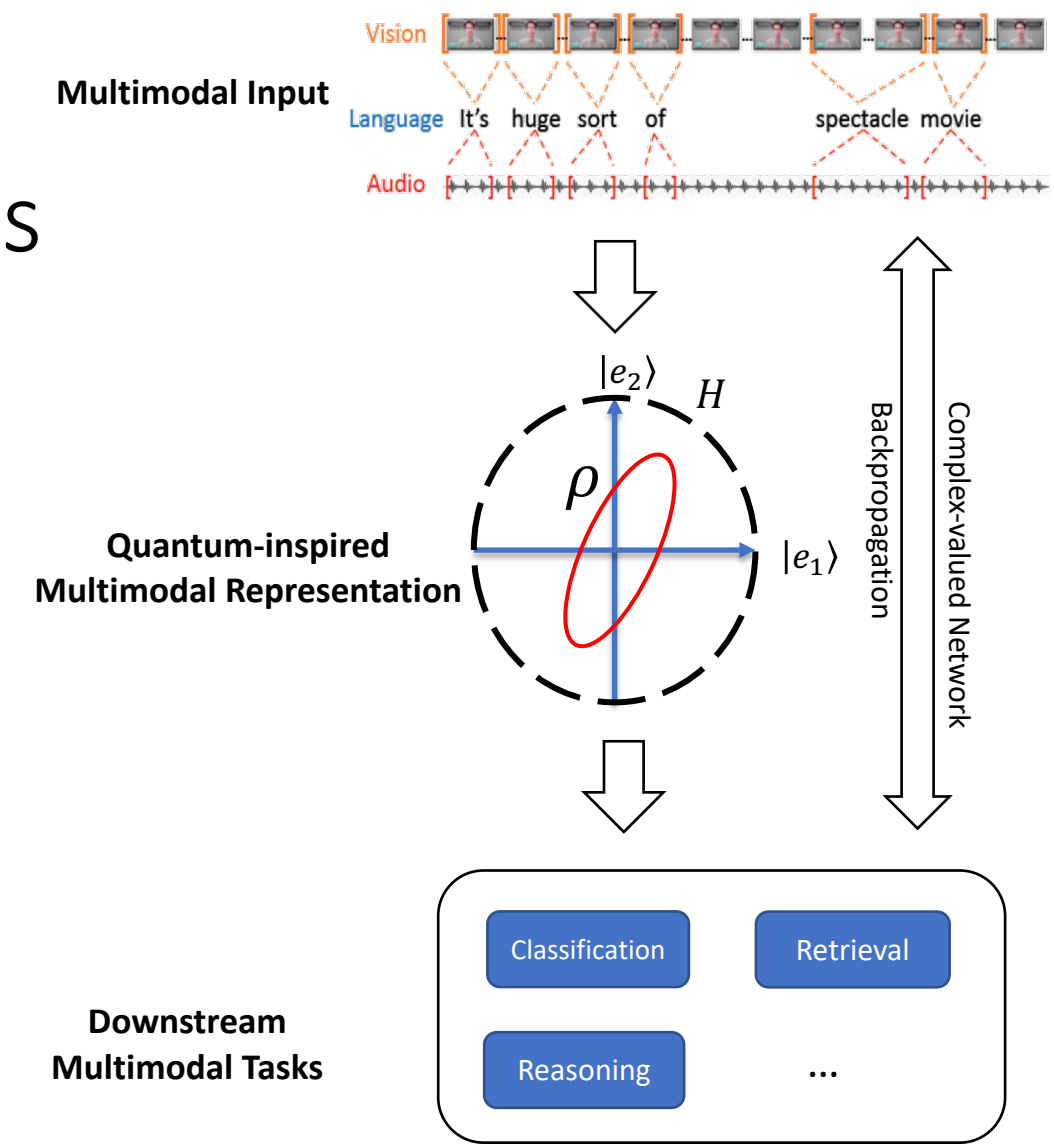
Research Problem

- Research Problem:
  - Human communications are conducted in different modalities (channels)
    - Textual, Visual, Acoustic
  - Sometimes this process is **complicated** and may involve **non-classical** phenomena
- e.g.
  - Acoustic: “aa-ba”
  - Visual: “ga-ga”
  - Combined: “da-da”



- The project aims at developing **novel multimodal data processing frameworks**
  - Explore **quantum theory** to model the interactions in different data modalities
  - Construct joint **quantum-inspired multimodal representation**
  - Design **quantum-inspired components** for downstream multimodal tasks

Impact and Applications



◆ Academic Impacts

- Novel theoretical approach for multimodal fusion
- New exploration of quantum-inspired models on multimodal data

◆ Industrial Applications

- Multimodal data processing systems
  - video emotion recognition system (prototype already in place)
  - video retrieval system

Decision Theory Based on Contextual Quantum Probability

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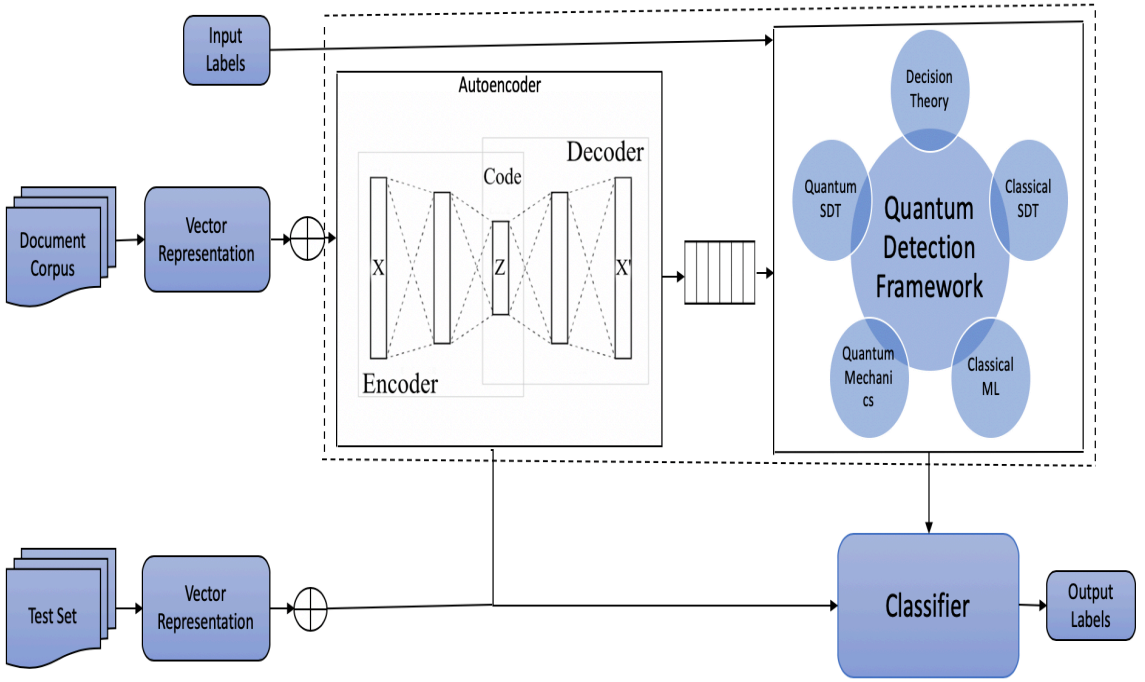
Quantum Detection Model for Classification

- Binary Classification
- Multiclass and Multilabel Classification
  - Decomposing such problem into binary classification



Research Impact

- QDM model improve the classification performance

References

1. Tiwari, Prayag, and Massimo Melucci. "Towards a quantum-inspired framework for binary classification." *Proceedings of the 27th ACM International Conference on Information and Knowledge Management*. 2018.
2. Tiwari, Prayag, and Massimo Melucci. "Towards a quantum-inspired binary classifier." *IEEE Access* 7 (2019): 42354-42372.
3. Tiwari, Prayag, and Massimo Melucci. "Binary classifier inspired by quantum theory." *Proceedings of the AAAI Conference on Artificial Intelligence*. Vol. 33. 2019.
4. Di Buccio, Emanuele, et al. "Binary classification model inspired from quantum detection theory." *Proceedings of the 2018 ACM SIGIR International Conference on Theory of Information Retrieval*. 2018.

Reasoning in Quantum Logic

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Introduction: Quantum Logic

- Physic defines logic (Quantum Physics $\rightarrow$ Quantum Logic)
- Logic is a set of rules that can be used to treat sentences.
- Quantum Logic is the logic of vector spaces, i.e., the lattice elements are closed subspaces (projectors) of Hilbert space.
- The join operation of two subspaces A and B is their closure (A and B and all their linear combinations), whereas the meet is their intersection.
- Generally speaking, QL differs from the logic of sets (Boolean logic) by violating distributivity. This violation makes QL more expressive.

Aims

- Quantum Reasoning is a kind of approximate reasoning that builds on quantum logic where the imprecision is modeled by quantum probabilities.
- The goal of the project is to define reasoning tools such as Quantum Implication that will allow us to reason with the data.
- Such reasoning tools are important to both Database and Information Retrieval systems -- they both use logic to achieve their tasks.
- Based on that, quantum reasoning could bring together DB and IR in one framework.

Entanglement of Semantic Entities in the Web

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About the Project

Entanglement of Semantic Entities in Corpuses of Documents

- Within a general approach to model human language by the mathematical formalism of quantum theory, we study '**entanglement**', one of the major fingerprints of the presence of quantum structure, in human language.
- We do so this by **identifying the violation of the Clauser Horne Shimony Holt (CHSH) inequality**, one of the form of Bell's inequalities, in corpuses of documents, such as COCA, NEW and Google Books, and **found a violation stronger than Cirel'son bound**.
- We are now setting up a **psychological experiment** with the aim of violating also stronger than Cirelson's bound the CHSH inequality and compare it to the violation we identified in the different corpuses of documents.
- We will use our findings for the **general quantum modeling of human language** ongoing in collaboration within the Brussels quantum cognition research group

Relevance to Academia and Industry

Contribute to a **general quantum model of human language**:

- Applicable to the domain where **natural language processing** is generally applied, such as ‘machine translation’, ‘speech recognition’, ‘information retrieval’, ‘meaning analysis’, ‘question answering’, ‘market intelligence’, etc…
- We plan specifically to engage in **analyzing medical data** to help working towards a possibility that ‘medical data analysis’ could form a more qualitative substitite for the actual gold standard of medical **evidence-based medicine**, i.e. the double blind tests

Quantum Statistical Distributions for Abstract Conceptual Data

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About the Project

- Use Quantum Theory and its capacity to describe:

(Indistinguishability – quantum particles cannot be distinguished from each other when, considered for human language - 'eleven horses', then 'each of the horses is indistinguishable of the other'), (Contextuality - quantum observables cannot be thought of as representing pre-existing values, when considered for human language - 'meanings depend on context', hence human language is contextual) (Superposition - different quantum states can be actualized at the same time, when considered for human language - 'pet-fish' e.g. 'guppy', meanings can be two at the same time (pet and fish)),

to model human language as a combination of concepts

- Technically introduce a Quantum Mechanical idea that a particle can only take on certain discrete values of energy, called **energy levels** that can also be applied correspondingly to **word rankings in texts** giving rise to the Identification of the Quantum Mechanical (Bose-Einstein) Statistics in human language.

https://rdcu.be/b1iLN

Aerts, D., Beltran, L. Quantum Structure in Cognition: Human Language as a Boson Gas of Entangled Words. *Found Sci* (2019). https://doi.org/10.1007/s10699-019-09633-4

Relevance to Industry and Academia

- Using the Formalism of Quantum Theory is effective when applied to
  Cognitive Phenomena that resisted Traditional Modelling.
  While the Traditional Modelling or Traditional Classical Decision Theory provides a significant understanding of cognition, researchers and findings gathered provide proof it is **inadequate to provide an explanation** to some of the **decision fallacies and judgemental bias**.
- **Improves the Natural Language Processing Tasks** like
  Natural language generation, Optical character recognition (OCR), Automatic summarization, Coreference resolution, Speech recognition, Text-to-speech Analysis.

Conclusion

Conclusion

- QUARTZ – Quantum Information Access and Retrieval Theory
- How can we utilize ideas inspired by Quantum Mechanics to improve search and text analytics?
- ESR Presentations (QUARTZ Young Radicals Group (YRG))

Questions?