Quantum Sensor Ontology for Accelerating R&D, and Comprehensibility

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ABSTRACT

Research and engineering in the quantum domain involve long chains of activity involving theory development, hypothesis formation, experimentation, device prototyping, device testing, and many more. At each stage multiple paths become possible, and of the paths pursued, the majority will lead nowhere. Our quantum metascience approach provides a strategy which enables all stakeholders to gain an overview of those developments along these tracks, that are relevant to their specific concerns. It provides a controlled vocabulary, built out of terms that are designed to be maximally comprehensible to all groups of stakeholders and across all the sub-fields of the quantum domain.

In this paper we 1) introduce our Quantum Science Organization (QSO), a not for profit group of quantum science and engineer volunteers and stakeholders and 2) list our QSO Charter, 3) overview our Quantum Ontology project and metascience, 4) consider approaches, including AI machine learning and the wildly investigated ChatGPT from OpenAI, 4) explain why Quantum Ontology is necessary to bridging the communications gap and accelerating progress in quantum science and engineering, 5) contrast ChatGPT to ontology-based AI, demonstrating ChatGPT inadequacies for the tasks at hand, 6) review the history of Quantum Ontology, 7) provide examples of quantum physics knowledge and application areas, and 8) preview the beta version of QSO's global secure infrastructure for developing and providing quantum knowledge as a service (QKaaS). Five recorded presentations by the QSO are accessible via the Video Index below.

1.0 INTRODUCTION: WHAT IS QUANTUM METASCIENCE

The state of quantum science today is comparable in many ways to the way things were in the life sciences at the turn of the present century. In both cases we are faced with a scientific revolution that is also an engineering revolution. In the life sciences, including clinical medicine, this was brought about through the completion of the human genome project, which created a scientific revolution in virtue of the new kinds of data which were suddenly made available in enormous quantities through an engineering revolution brought about through the invention of new kinds of devices from DNA/RNA/protein purification and extraction systems, sequencers, genetic analyzers, mass spectrometers, and many more. How were clinical and other life scientists able to exploit these new forms of data for diagnostic and therapeutic purposes, where the significance of the data for the understanding of human health and disease still needed to be determined? How were engineers to discover the possibilities for generation of new kinds of -omics data that would be maximally useful to clinicians?

parallel scientific-and-engineering revolution in the quantum domain needs, in this audience, no explanation. The problems it causes are also similar. Here we have a range of stakeholders: quantum scientists and engineers, funding organizations, investors, market analysts, users of quantum devices. All of them are faced with the same long chains of activity creating a many-threaded near-anarchy of alternative paths to quantum success, complicated, in some areas of least, by the fact that we are competing with an adversary, whose dominance in the quantum sphere would bring immense consequences for the future of our civilization.

Quantum metascience (Figure 1) is here proposed as a contribution to the solution of these problems. It draws on the solution developed in the -omics sphere already around the turn of the century and applied since then in multiple clinical and life-science areas through a multi-billion-dollar investment from government and private (mainly pharmaceutical) industry. This bio-metascience provides an ever-growing analysis framework for understanding the highly complex sequence data generated in the -omics sphere in terms understandable to human beings. These terms are managed in a controlled vocabulary, initially codified as the Gene Ontology (GO), which was seen from the very start as a 'tool for the unification of biology'. The GO supplies a consistent carefully curated set of terms for describing cell types and molecular and biological processes, terms which have been used to annotate (or 'tag') vast quantities of -omics data and related literature. Over time the GO has been augmented by other controlled vocabularies in domains such as anatomy, disease, proteins, and many more, to form the OBO (for 'Open Biological and Biomedical Ontologies') Foundry. All terms in the Foundry ontologies are provided with both human-readable and computer-processable definitions, so that bodies of data which are annotated via OBO become themselves computer processable, in ways which now provide hundreds of vital channels for clinical and other forms of data analysis.

In more recent years the methods developed and tested by the OBO Foundry have been extended to other areas, including defense and intelligence, and industrial manufacturing, and they are now being applied in the quantum domain through the development of new controlled vocabularies. First, is a suite of foundation ontologies:

- mathematics ontology
- physics ontology
- physics experiment ontology
- units of measure ontology

These will provide the basis for:

- quantum physics ontology
- quantum engineering ontology

All ontologies will be developed following the methodology outlined in ISO/IEC 21838, which is designed to ensure interoperability not merely of ontologies, but also of the data tagged using their terms.

In what follows we will describe what we call 'Quantum Metascience', based on these ontologies, which will pursue a mammoth data-tagging effort, involving both human data curators and, wherever this is possible, machine curation (semi-automation) (Figure 2).

Quantum metascience will extend over all areas of quantum physics, quantum computing, quantum communications, quantum sensing, and many more, with the goal of allowing different communities to gain a synoptic picture of quantum developments along all dimensions pertinent to their goals and concerns.

2.0 A BRIEF HISTORY OF ONTOLOGY

The term 'ontology' has a long history in the literature of philosophy, where it stands for what is otherwise referred to as 'metaphysics', a branch of philosophy initiated by Aristotle in around 250 BC. The term acquired a new shade of meaning with the work of the American philosopher-logician Quine, who coined the phrase 'ontological commitment' to refer (roughly) to: the entities whose existence we commit to when we logically formalize a scientific theory. In the 1970s the term in this sense was taken over by the group around John McCarthy working on early ('logical') AI in Stanford. In particular Patrick Hayes, in his Naïve Physics Manifesto, applied the term to describe the ontological commitments of human common sense, the idea being that if we could formalize how humans classify entities in the world, we could use this information to program human common sense into a robot. These experiments in robotics, which used the standard 'first-order logic' established by philosophers, failed. But the basic idea is still alive today, not least in the Siri app in your iPhone, whose creator, Tom Gruber, was a member of this same AI group in Stanford.

The underlying idea of Gruber and others was that one could use common ontologies as a means of making information collected by different groups shareable. This led to the creation of KIF (for 'Knowledge Interchange Format'), which was designed to promote the interchange of knowledge between systems – or in other words to create data and information system interoperability. It is this which has been the goal of computational ontology research ever since.

The next big step was the creation of the Semantic Web by Tim Berners-Lee and his associates, and thereby also the creation of OWL (for 'Web Ontology Language'), which is now one of the three major vehicles for the formulation of ontology content, the others being RDF (for 'Resource Description Format', now used extensively in knowledge graphs, for example in Linked Open Data), and Common Logic (an international standard version of first-order logic adapted for use by computers). Common Logic has the advantage of high expressivity; OWL has the advantage of an efficient reasoner.

Already in around the year 2000 there were numerous ontologies in existence based on predecessors of OWL. Each had its uses, and its users. On the other hand the proliferation of ontologies defeated the very goal of information system interoperability. Interoperability fails already because the ontologies themselves created siloes.

Also in around 2000, and independently of the aforementioned developments, there arose in the field of biomedical informatics something called the Gene Ontology, a controlled vocabulary for use in the life sciences – including medicine – to provide interoperability across the many data and information systems unleashed by the Human Genome Project. A presentation by the Quantum Science Organization on the History of Ontology, with timeline, can be seen in Video 1.

3.0 WHY THE QUANTUM METASCIENCE INITIATIVE (QMI)?

Our goal for the Quantum Metascience Initiative (QMI) is the achievement of the following quantum objectives identified already by a responsible government agency: quantum secure by 2027, quantum ready by 2030, quantum advantage by 2035. To do this, we need to address several potential hindrances. First, the complexity of the topics as well as the sheer number of researchers and publications can hinder interested parties from being exposed to the highest quality research at the speed needed to advance science and collaboration. In 2009, Bettencourt et al., conducted a study analyzing the correlation between overlapping literature topics and research collaboration over 8 scientific fields [1]. This study found 8946 articles written by 7518 different authors [1]. A similar study conducted by Seskir et al. in 2018 for the quantum domain alone found 49,823 articles but a mere 34 core publications [2]. This high rate of growth around a relatively small set of core literature items illustrates just some of the sorts of problems which will be faced by those interested in quantum initiatives, who under current conditions need to conduct their own pain-staking and time-consuming searches for applicable information. The QMI is designed to provide a tool for the solution of these and a whole series of related problems (Figure 3).

Second, the collaboration of subject matter experts does not extend across global boundaries. Two initiatives of note are the Responsible Research and Innovation (RRI) package within the Networked Quantum Information Technology (NQIT) project and the European Horizon 2020 Project. The NQIT project sought to enable partnerships with responsible scientists at all levels while ensuring rigorous science and anticipating future social transformation within the United Kingdom. Since its inception in 2016, the NQIT project has generated two reports, a policy brief and a small number of publications [3]. While this project has produced valuable information for responsible quantum research, the focus of collaboration and research policy has been centralized on United Kingdom efforts [3]. The European Horizon 2020 Project is a one-billion-Euro grant joined by 38 academic, industry-oriented research institutions, non-profit organizations, subject matter experts, and large enterprises [4]. The goals of this project are:

1) Consolidating and expanding European leadership and excellence in quantum technology research
2) Kick-starting a competitive European QT industry
3) Generating opportunities for innovative businesses and investments in QTs
4) Creating radically improved solutions across many domains (including energy, health, security, and the environment) for the benefit of society and the individual [4]

Realization of these goals can be beneficial for the entirety of quantum research stakeholders, but, as here, the focus is narrowed to just one part of the global community. Lastly, publications on concentrated areas of interest within quantum initiatives are not equally represented in current automated search parameters. Even studies on literature within specific quantum technologies show limits within the time- period and search query parameters in addition to a focus on certain sub-areas where those technologies are applied [2]. Seskir et al. found only three areas of concentrated interest within their search on the Web of Science: physical realizations, quantum cryptography/communication, and quantum computation with quantum information theory concepts [2]. Seskir et al. used their own expertise to formulate extended search parameters to include areas such as quantum sensing [2]. Their work also showed a shift from computational and theoretical quantum subjects to diverse topics that built upon theoretical foundations topics [2]. Despite the expert review, quantum sensing had the lowest weight in the updated parameters [2]. This shows how much literature reviews in the field of quantum sensing, due to its interdisciplinary nature, could benefit from expert review [2]. In their literature search, Bettencourt et al. determined quantum computing "was a field without a unified conceptual framework, and as a result even as it grew slightly it did not densify" [1]. This lack of densification within quantum technologies research, recognized already in 2009, illustrates the degree to which opportunities are lacking for collaboration in such research.

QSO's Quantum Metascience Initiative (QMI) seeks to address these roadblocks while establishing a roadmap to achieve common strategic objectives (Figure 4). A standardized synoptic overview is needed to expose areas of research overlap, to identify gaps and to associate these with measures of urgency which can be used to prioritize support, and for development activities [4]. On a small scale, QMI can help overcome compartmentalized information sources such as an overreliance on physics journals by linking field-specific journals and preprint archives, algorithm catalogs, and other sources to information at all levels relating to quantum technologies [2]. Identified gaps can include gaps in protocols, measurement procedures, modules for methodology standardization, and security implementation, all which can hinder future quantum technology initiatives and collaboration [4]. Additionally, establishing a framework for overviewing quantum technologies research can reveal relationships within various collaborative networks and show overlaps within shared fields [1]-[4]. QMI can help in addition to establishing and publicizing relationships among institutions within a country or countries resulting in better advice on investments, commercialization, policy and collaborations [2]. A standardized overview framework can help to align stakeholder motivation and define policies among industry and research leaders [6]. QMI can also promote stability and innovation in various geopolitical environments [6]. Current literature review studies based for example on the Web of Science can to a degree reveal potential areas of cooperation, but they fall far short of what could be achieved with the facilities of the QMI. Similarly, what can be achieved through networks for stakeholder collaboration is limited by the small number and limited scope of such networks [5], and QMI provides here also an opportunity to expand and accelerate.

Our goal is for QMI to be a central knowledge portal for all sources of quantum-related knowledge and tools while bridging the gap among specialized disciplines of physics, such as mechanics, electrodynamics, photonics, and among specialized applied disciplines such as sensing, computing, networking, and other relevant knowledge for quantum technology stakeholders. Our metascience and ontology approach forms the foundation of quantum knowledge as a service (QKaaS).

Some will argue that the goals of QMI will before too long be achievable by AI, for example by sequential large language models (LLM), such as ChatGPT. Our experience with practical ontology building in different areas, however, and also with attempts to use LLMs to provide the sort of reliable standardized information that ontologies need, casts considerable doubt on such expectations. We draw lessons from the recent decommissioning by Meta (Facebook) of their Galactica tool, whose goals were in some ways similar to those of QMI, though extended across a much, much broader range and excluding the critical contributions of human beings. (Note: we also draw lessons from our own research, by Landgrebe and Smith, on the mathematical limitations of AI when it comes to complex systems such as scientific or technological disciplines [11]).

At the same time, we can use powerful machine learning and related tools to populate major parts of the QMI portal, but the instructions of what and how to populate need to come from human beings with the corresponding quantum expertise.

AI models can merely output sequences which approximately correspond to the language distribution found in the training corpora, used for the creation of the unsupervised core foundational models, and the subsequent refinement of specialized models using supervised learning. They are unable to create reliable output (in which the propositions are true in the given context and according to our current scientific understanding), and do not perform well even in basic sequence generating tasks in language and knowledge domains that are underrepresented in the training corpora. Let's look at two examples: ChatGPT and Galactica.

While ChatGPT has quickly become a highly used AI application, there are both benefits and drawbacks. Early adopters have found ChatGPT to be beneficial in helping draft texts [7]. We have found ChatGPT providing alternative formulations to the original text when writing a patent application. However, in a separate test using ChatGPT to draft statements on quantum science, ChatGPT generated erroneous surface-level ideas. One sample statement is "Quantum science is an incredibly powerful and useful branch of science, yet it is also highly confusing to many people. This is because Quantum science deals with phenomena which are not easily understandable and involve principles that contradict the laws of physics as we know them." This illustrates the core weakness of the algorithm: It creates output which is plainly wrong because of course, quantum physics provides valid laws of nature. The problem is rather, we do not really know what it is, that the valid mathematical models describe.

ChatGPT can also be used as a search engine that presents sought-after information in simple terms [7]. In our own research, ChatGPT was able to accurately report on the various types and applications of quantum sensors. ChatGPT was also able to provide surface-level information on metascience and methods to advance quantum technology. One example of a search result from ChatGPT, on advancing quantum technology, is "Collaboration and partnerships: Collaboration and partnerships between researchers, businesses, and other organizations can help to accelerate the development of quantum technologies by pooling resources and expertise." Our examples, coupled with previous user experience, supports limited use for AI such as ChatGPT, within collaborative efforts.

However, it is within these two areas that ChatGPT's drawbacks are seen. When writing text, ChatGPT is not capable of understanding the context, or the meaning of the text it generates [8]. Egger et al. observed "suggestions and sentences generated by ChatGPT may not always be relevant or accurate and may require additional editing and proofreading by the writer" [8].

As a search engine, ChatGPT may personalize recommendations that create algorithmic bias, reinforcing existing biases or perpetuating stereotypes [9]. Our user experience found ChatGPT exposed the user to information without references to specific sources, potentially making its information untrustworthy. In its current construct, ChatGPT lacks a rigorous ontological framework, and has limited ability to see beyond the immediate context of a particular query.

Now to Galactica. Meta management claimed that galactica.ai "can store, combine, and reason about scientific knowledge" and perform tasks such as solving equations, summarizing scientific texts, or searching for relevant literature. This would mean that the AI would act like a superhuman polymath able to understand and evaluate the most intellectually demanding text that humans can produce.

Gary Marcus commented that such AI-based language models are "confabulate math and science. High school students will love it and use it to fool and intimidate (some of) their teachers. The rest of us should be terrified." (See samples of the nonsense the model produces.). In short, Galactica failed on all its promises – as the international scientific community quickly realized – and Meta has now discontinued the service. Such language models fail because they do not understand the complexity of human language. Instead, they model sequences of symbols without the ability to interpret their meaning. In a deep sense, they can never achieve the understanding of meaning, because meaning requires consciousness and intentions: "What does this mean for me?" is the question which we consciously and unconsciously ask ourselves when we encounter a unit of language or a symbol (e.g. a stop sign or a crucifix). But machines have neither consciousness nor intentions, they merely execute calculation patterns, albeit very complicated ones [10].

While QSO's Quantum Metascience Initiative (QMI) does not currently have the capability to create new content on its own, it does effectively link collaborators to each other based on shared interests, collect and pre-process what is needed for quantum ontology development, and task and collect ontology fragments from QSO members. Moreover, the human element will always need to be part of the knowledge-producing process to effectively and accurately convey complex scientific thought.

4.0 QUANTUM METASCIENCE ORGANIZATION CHARTER

The Quantum Science Charter is listed below:

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1	Explore tools, techniques and procedures (TTPs) for potential applications for accelerating QS&E and advancement
2	Develop the Quantum Ontology
3	Recruit quantum subject matter experts (SMEs) for development of parts of the ontology that are pending development
4	Provide Quantum science organization, (QSO) Portal to members
5	Facility to allow users to ingest data and information, and use natural language processing (AI), to generate Ontology-based Knowledge Graphs

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6	Provide highly secure, global access, and high availability for a QSO portal that is easy to use.
7	Solicit wide participation and enough resources to complete a high-quality Quantum Ontology, capable of becoming ubiquitous within the QS&E community, and the global de facto standard (ISO/IEEE)
8	Provide a Rapid Response Capability via member experts (paid), to do quantum science and engineering tasks, quantum communications, quantum sensing and quantum computing, as needed by stakeholders
9	Publish papers and a book to transfer knowledge about quantum science and engineering, and QSO, and its initiatives that promote adoption and new members and sponsors
10	Participation in major events where quantum is relevant, such IEEE, SPIE and the Quantum Economic Development Consortium (QED-C)
11	Facilitate sharing information, like research results, and prototype and products specifications, metrics, intellectual property rights and other relevant information.
12	Collaborate and partner with industry, government and academia
13	Provide opportunities in Quantum career tracks
14	Catalog and advance quantum use cases that have high-value potential, with priority for member stakeholders (funding institutions and beneficiaries) and provide the tools and access for doing Quantum Technology Assessments via the QSO Portal.
15	Provide a Quantum Technology Pipeline and tools that can be maintained globally and used via the QSO Portal, and other activities with potential for accelerating quantum progress, communication between disciplines and communication with stakeholders.
16	Provide knowledge: quantum knowledge as Service (QKaaS), via the QSO Portal
17	Apply AI machine learning and discovery to the ontology-based knowledge graph within the QSO portal; the ontology-based knowledge graph is an ideal source because all data and information is linked by ontology-based terms and relationships.
18	Provide means to assess progress in AI and apply modern AI machine learning approaches as they mature.

5.0 QUANTUM ONTOLOGY

We saw that ontologies a) are representations of knowledge which give an overview of a scientific field, b) enable a classification of all its contents, and c) can create transparency within a scientific domain and across domains. They can be used to create and query knowledge bases, and can also be used to obtain transparency on funding and status of public investment usage. They can be used to drive collaboration, and allocate funding in a rational manner, like in a distributed scientific mega-project comparable to the ISS, the Manhattan project or the CERN project.

Technically implemented ontologies consist of an abstract layer which corresponds to the knowledge of a domain (and partially the information layer), and an instance layer, which corresponds to a layer of real data. In description logic, the low-expressivity computable logic and taxonomy model underpinning the W3C ontology standard OWL2, are the a) abstract layer called T-box (terminology) and b) the instance layer is called A-box (assertion). For example, "physicist" is an entity from the T-box, and "instanceOf(physicist, Albert Einstein)" is an A-box assertion in triplet form. One of the challenges in creating technically usable ontologies is the design of an abstract layer.

Ontologies enable the organization of knowledge for both expert and non-expert stakeholders. While each expert in quantum physics and quantum engineering (for example a solid-state physicist and a quantum sensor engineer), know their domains perfectly, and do not need an ontology to organize and query their knowledge, the public and private administration of science needs ontologies, to understand how the science is organized, and what the dependencies between the various disciplines are. This enables rational management of funds and big projects. Ontologies can also help specialists get acquainted with new research topics more easily.

The main aim of this Quantum Metascience Initiative (QMI) is the generation of quantum ontologies for knowledge organization, search, and administrative usage.

An ontology of quantum engineering needs an ontology of quantum physics to describe the models that underpin the engineered technical systems, in other words, the quantum physics and engineering ontologies describe the dependencies of quantum engineering (see Fig. 3). A quantum physics ontology, in turn, depends on an ontology of physics and mathematics. Physics needs mathematics because since the late 18th century, the formal models of physics are all formulated using mathematics.

By exactly showing the dependencies of quantum engineering technical systems from quantum physics (and other engineering disciplines), quantum engineering budget planning and prioritization can be optimized. Quantum engineering covers all applications of quantum physics from solid state engineering to quantum communications, quantum sensing and quantum computing.

The physics ontology underpinning the quantum physics and quantum engineering ontologies comprises three branches: system entities, magnitudes, and models. Systems are collections of dynamically interrelated physical elements participating in a process. All systems are fiat and created by human delimitation. To delimit a system is to select a level of granularity of its elements, from microphysical particles to entire galaxies. In classical physics, magnitudes are phenomena in reality -- for example weight, distance, velocity, acceleration, or energy -- which have the feature that their instances can be measured. In quantum physics, magnitudes such as the spin no longer fall within the domain of what can be imagined using common sense. Rather, they can be understood only mathematically, via the use of models. But these models still describe properties of real entities. Models are representations of an aspect of reality using abstract symbols that are created to describe, explain, or predict the aspect of reality in question. The core of a model in physics that enables engineering is always a mathematical model (all the parts of which come from the ontology of mathematics).

Figure 5 informally illustrates how a quantum device can be shown in ontological context. It illustrates that the device in question, the superconducting quantum interference device, SQUID, is a system with a Josephson junction, which is a superconductor-based technical system. The magnitude branch shows some of the magnitudes required to describe a SQUID and measure its physical properties. The model branch contains a taxonomic model hierarchy of the mathematical models used to design a SQUID. The mathematics ontology from which the model components are taken is not shown, and neither is the relationship to common-sense ontologies such as BFO.

Once relevant fields of quantum engineering are modeled ontologically, it will become much easier to organize the knowledge of the field for project planning, budgeting, realization and management purposes (Figure 6 and Figure 7).

Further details are contained in past Quantum Science Organization (QSO) presentations found in Videos 2 and 3.

6.0 QUANTUM SCIENCE ORGANIZATION'S PORTAL

The objective of the Quantum Science Organization's (Figure 8) infrastructure and portal is ease of use, not only for the quantum science and engineering (QS&E) community, but also those who can benefit from the products and services from QS&E performers. It is as secure as bank accounts and has access points in multiple locations on every continent. Anyone can create an account, but what a user will be able to do will depend on the user's role. Portal partitions will accommodate various kinds of users: a) ontology developers, b) content providers, c) stakeholders (funders and beneficiaries). These partitions are necessary because the kinds of tools and services differ between types of users. Some tools are common to all, such as knowledge as a service (QKaaS) described below. Precision search and discovery is a capability on top of the ontology-based knowledge repository, and exact matchups of things like funding source's requests for information (RPIs) and requests for proposal (RFPs) are a feature of this capability. The ontology-based knowledge representation is conducive to full utilization by man and machine, such as above, and for machine learning etc.

The QSO is addressing several open questions, such as how to facilitate a) development of the Quantum Ontology that is robust enough to be useful globally across all of the quantum discipline and end-user use cases, and b) engagement with the international community on topics such as research, engineering, international standards, product development in ways that allows for friendly scientific arguments and consensus building along the way. In this regard, infrastructure is one of the three legs of QSO's Quantum Metascience Initiative: people, knowledge, and infrastructure, to connect the other two, and provide near-full capability with easy, responsive, user-friendly access from anywhere on the globe.

Quantum knowledge as a service (QKaaS) will be developed on, and provided by, the QSO Portal. The QSO Portal is being equipped with numerous capabilities that will be available in tandem with publication of a book. The book will cover the aspects of quantum science and engineering (QS&E). The QSO Portal, which is up-and-running in early beta, provides for the collection of information for this initiative. When fully deployed it will do the pre-processing of the knowledge, information and data required for the Quantum Ontology development. It will provide information sharing and collaboration for Quantum Ontology development, and version-controlled publication to the web. For information sharing within a user's account, a user can simply "drag and drop" files from a folder on her workstations, or cloud, onto the portal Upload page. Files, if not in English, are automatically translated from 75 different languages into English. Within the user's account is a suite of tools and resources, via a Resources menu option on the QSO Portal homepage, that has several submenu selections for a) digital library b) exploratory activities such as access to the quantum algorithm zoo, c) glossary, d) interactive knowledge graph that serves as a placeholder for the yet to be completed Quantum Ontology, e) knowledge graph browser and f) knowledge graph query engine. During beta the QSO Portal is being improved with beta user feedback. When fully deployed it will also have tools for validation of user submitted content, such as parts (fragments) of the ontology, to ensure that only accurate information is being synthesized. Users can volunteer for tasks, such as paid ontology development, for members and other volunteers to provide parts (fragments) of the Quantum Ontology. Users are encouraged to use the Survey menu option in the portal for evaluating the research questions that this initiative is addressing, and helping assure that this initiative is addressing the top priority needs of the QS&E and stakeholder communities. For example, survey results are used to keep this initiative on track with the requirements of funding organizations looking to advance the technologies in the Quantum Technology Pipeline. The Quantum Science Organization also believes in being lock-step with artificial intelligence and machine learning. For example, arguably the most advanced AI tool, ChatGPT from OpenAI, is accessible on the portal for evaluation purposes. As shown above, its utility is very limited, but QSI is monitoring progress on reportedly "best" of AI machine learning, like OpenAI and Google's Deep Mind, as capabilities evolve.

The QSO Portal's Profile page (menu option) is where users select ontology terms to describe their interests and expertise, or they drop a document with this information on the Upload page, and it ingests semi-automatically. If not in English, the system detects the language and translates it to English (75 supported languages). The items in the knowledge graph have the high-fidelity ontology-based labels. All is in the same ontology-based accurate language, removing the ambiguity of conversational language. Precision Queries & Matchups result from the consistent accurate labeling. For example, stakeholders are afforded accurate, complete inventory from the quantum technology pipeline, because of this precise language. This applies also to pushing quantum news, like quantum breakthroughs, to those who have requested it (via their QSO Portal selections), because their interests are labeled in detail, in precise, ontology-labeled (tagged) language of the news, research publication, and other quantum information that has been ingested into the knowledge graph. Users can activate/select (or deactivate some/all items) of the automated pushes. This is all made possible because of the same high-fidelity quantum ontology labels. As the Quantum Ontology is developed, this kind of capability increases the utility for both the quantum experts and stakeholders alike. One high-value example is AI machine learning for discovery, that can be performed on the data that all has the same, uniform, standard quantum ontology-based labels. The QMI Portal is deployed with Amazon Web Services, providing it with, for all practical purposes here, unlimited scalability and compute power. The Bracket quantum computing environment and large quantum algorithm library can be accessed directly from users' accounts, as needed for quantum metascience initiatives purposes. A walk-through of the QSO's beta portal, including drag-n-drop Upload, Knowledge Graph, Survey etc. can be seen in Video 4. QSO is collaborating with industry, government and academia. The first two are combined, and the third is highlighted as a separate section because it deserves special attention. It contains a university collaboration discussion in the Video #5 below.

7.0 ACADEMIA, INDUSTRY, AND GOVERNMENT

Many QSO volunteers have day jobs with Government employers, such as NIST and DIA. Volunteers cannot use their employer's resources, nor charge labor hours, except when authorized by their respective employer, whether government or industry. All volunteers are encouraged to inform their employers of professional extracurricular activities. To date all Government employees that are also QSO volunteers have had no (zero) issues with volunteering their time. QSO is non-profit, and it is serving the best interests of the quantum professional community, and those who can potentially benefit from quantum technology, such as stakeholders like funding source organizations that are looking to advance quantum technology from lab-to-field.

The major difference between industry and government is in sponsorship opportunities. Industry can contribute at Platinum, Gold, Silver, Bronze sponsorship levels that are described elsewhere, and government is typically grants and contracts, although this is an option for industry also. Engagements to date have included conferences at IEEE and SPIE, and meeting with the Quantum Economic Development Consortium (QED-C). QED-C is significant because of its extensive reach: quantum performers/members from about 37 countries. QSO presents at the NATO Military Sensors Symposiums in April 2023. QSO has also met with quantum providers directly, ranging from startups to Fortune 500 companies. Today there are over 500 quantum performers globally and QSO is routinely cataloging more as they enter the quantum landscape.

There is continually an expanding need in intelligence to collect data in forms which will allow aggregation and reasoning. More specifically to create interoperability of data repositories and data resources. Ontology development efforts address this need. Until recently these efforts have been fragmentary. Now, however, we have the Department of Defense and Intelligence Community Ontology Working Group (DIOWG), which has recognized a need for a coordinated effort, with high level (Chief Technology Officer, Chief Information Officer, etc.) spearheading the support. The work described in this paper falls under the auspices of the DIOWG.

Collaboration with the National Intelligence University (NIU) establishes a basis for rapid advancement in later stages of the students' careers. This project includes a large edifice of quantum ontology-based labels which provides opportunities for students to familiarize themselves with data curation needed for real world applications. With an early adoption the students will have the opportunity to contribute to all aspects of quantum metascience including ontology development, ontology evangelization, ontology software applications, and Artificial Intelligence related software.

Students can contribute to the QSO's quantum metascience initiative (QMI), by supporting data ingest into the knowledge graph, including the quantum sensors pipeline portion. This is essentially a database population of all institutions, subject matter experts, specs, metrics, and intellectual property rights etc. linked together as entities and relations, without the disjointedness of relational tables. This seemingly daunting task is eased via the automation features provided by the QSO Portal. For example, when the portal (currently in beta) is launched for students use, it will provide the automated drag-and-drop onto Upload portal page, ingest, and parsing of the documents. If a document is not in English, and in one of 75 supported languages, it will be automatically translated and parsed also, as part of the knowledge ingest process. Students' time will be more intellectual, spending less of it on mundane tasks, such as the raw knowledge ingest from a) quantum knowledge sources and b) prototype/product developers spec sheets, and c) text contained in documents and websites.

Under the guidance of NIU faculty, the students will be able to organize cohort lead research in an environment where they can focus on assessing technical capabilities, performance, use cases, and technical readiness of the respective sensors in the pipeline, including editing and reviewing specs and metrics, assessing, and selecting from the portal page drop-down list of the 9 technical readiness levels. Furthermore, they will be able to provide additional content to the quantum knowledge base, helping to expedite transfer from lab to deployed real world applications, as quantum technology matures. With faculty and students' involvement, and collaboration, their contributions will provide additional curated content, thus added-value, for industry, government and academia alike.

The National Quantum Initiative Act (NQI Act) was signed into law on 21 December 2018. It directs the President to implement a National Quantum Initiative Program to establish the goals and priorities for a 10-year plan to accelerate the development of quantum information science and technology applications [12]. Since the establishment of NQI there have been three annual reports published on the NQI program, the latest report released on 6th January outlines some important guidelines and achievements in FY22 [13]. The NQI promotes engagements with industry, the academic community, National Laboratories, and Federally Funded Research and Development Centers.

The third annual report on the NQI program and budget outlines a sustained investment by the establishment of several NQI centers, the Quantum Economic Development Consortium, and new Quantum Information Science (QIS) R&D activities. The reported actual budget expenditures for Quantum Information Science (QIS) R&D were $449 million in FY 2019, $672 million in FY 2020, and $855 million in FY 2021, and $918 million in FY22 [13]. The requested budget for FY 2023 is $844 million which highlights the sustainability of the NQI program for the near future. The focus and future investments made in fundamental QIS research, education, and training across agencies and departments will be crucial on society and ways each organization accomplishes its mission. The QMI initiative is aligned with NQI to develop an ecosystem that will accelerate the body of knowledge by promoting discovery and exploration through partnerships with academia and industry.

The National Strategy for QIS recommends strengthening the U.S. approach to QIS R&D and to focus on six key areas: science, workforce, industry, infrastructure, security, and international cooperation [13]. Implementing a science-first approach requires strengthening core QIS R&D programs, promoting new QIS centers, and exploring quantum frontiers. The QMI initiative is relevant across the agencies, departments and QIS centers in many regards, especially the sharing of information via the ontology-based knowledge graph. QMI members engage on important issues within the QIS community, and the QMI Portal (currently in beta) is expected to make engagement easier, and improve the efficiency, effectiveness and speed of information synthesis and dissemination, thus improving the speed of quantum innovation. AI machine learning applied to the QSO ontology-based knowledge graph, described above, should help accelerate discoveries and progress. It is too early to know the full extent of AI machine learning on this, but evidence suggests that it will be very significant based on remarkable advances in AI machine learning in recent years.

QSO's Quantum Metascience Initiative (QMI), in coordination with the National Intelligence University, will be co-hosting a "Quantum Metascience'' engagement at the university in spring 2023. The QMI and NIU will be joined by professors, staff, and experts in S&T intelligence education, diversity, equity, and inclusion for a series of brown bags and guest lectures aimed at exploring specific actions needed to ensure progress in quantum education as it relates to national security.

QMI researchers will be engaging with NATO to discuss joint interests and collaboration opportunities in quantum science, engineering and QIS at the 10th Military Sensing Symposium in April 2023. In addition to identifying several QIS areas of mutual interest, it is anticipated that QMI symposium attendees will hold a series of discussions on QIS use cases with the goal of furthering this collaboration and identifying quantum technology solutions to existing real-world problems.

8.0 CONCLUSION

The original motivation for the Quantum Metascience Initiative was the Great Race to quantum dominance. Now that the initiative has been established it has become clear that it is something that is needed by quantum science in and of itself, as well as by quantum engineering and by all the stakeholders. In other words, it's needed even if there was no Great Race. But given that we are in this race and given that the stakes are far too high to lose, this initiative is essential. The mission is to accelerate progress and facilitate communication between quantum science and engineering, and stakeholders. The latter includes those funding the research, developers, potential end-users of applications, intelligence analysts, investors, and many more. The QSO Charter is broad, but at the core is ontology, and the quantum knowledge as a service (QKaaS) that results. The history of applied ontology was overviewed above and in Video 1. This current initiative draws on two decades of progress in this field. We reviewed the quantum ontology in the text and in more detail in Videos 2 and 3.

The three pillars upon which this initiative is built are: 1) people (experts in ontology, in quantum science, and in quant engineering), 2) Quantum Ontology and the Quantum Metascience that is built thereon, and 3) the QSO Portal. The portal is the enabler which allows people to draw on – and contribute to – the growing body of data and information that is created through application of the Quantum Ontology to data relating to all quantum-relevant concerns. Uses of the portal include a) precision query, and discovery, from the ontology-based graph knowledge base, b) support for AI machine learning for discovery research, and c) more specialized tools, available from secure QSO Portal accounts, depending on user's role. The portal is currently globally accessible in beta, and users can create accounts now, but the features described above will not be officially launched and available to the community until a related book publication project is completed and the book released (scheduled for later this year).

The Quantum Science organization (QSO) is currently embarking on a University Collaboration Pilot project (Figure 9) with the National Intelligence University (NIU), whose goal is to recruit students to work on this initiative (using the QSO Port) to supplement their studies in the quantum field. An example is a cohort of students supplementing their theoretical work on the physics of quantum sensors, by exploring quantum performers engaged in quantum research and development of quantum prototypes and products. As they learn more about these prototypes and products they would enter the corresponding data into the portal, using semi-automated ingest tools to minimize workload in linking technical data with information already contained in the Quantum Knowledge Graph at the application (device) level, and the overarching Quantum Ontology at the theoretical level. In this way, the students would begin to see the practical relevance of their theoretical studies in a new way, while at the same time building expertise in ontology-based research and applications.

Essentially everyone that develops or uses sensors, computers and communications networks is touched by this initiative in some way. For example, a developer of sensors probably only knows classical sensing, and will be enlightened on quantum sensor counterparts, if they exist for her application. However, note that Quantum is only applicable sometimes.

The seemingly daunting task of orchestrating the above is realized efficiently and effectively via the globally accessible, secure and capability rich QSO Portal. Consider this scenario: a classical physics systems engineer somewhere on the globe is developing a product and needs a sensor for navigation. She queries the future Quantum Technology Pipeline, or submits a request for information (RFI) request that contains full requirements, to the Quantum Technology Pipeline (represented in knowledge graph with graph query engine). It yields no results. This is still valuable information: there are no classical counterparts for her current application. However, in some cases, there will be one or more quantum counterparts. With the push of a button she can get a high-fidelity comparison of matching quantum sensors, and all matching classical sensors. Because of the ontology-based knowledge graph, the results are a list of very detailed specs, metrics, IP rights (and more) terms are displayed in tabular form, in column A. To the right, the remaining columns display all the matching classical and quantum sensors, with percentage differences on performance. Within seconds the classical developer is fully aware of the potential quantum alternatives, their technical readiness levels, ranging from TR level 1 to level 9, and whatever other data that has been requested, assuming it has been ingested into the knowledge graph; if not, that cell of the table is empty. Missing data can be updated by the QSO Portal user(s), and the user can run the comparison again. Some will argue that this can be achieved in other ways, such as a relational database, but the knowledge graph approach here has many advantages, the first of which is complete integration of data rather than disjointed, relational tables, and it is ontology-based. Another is that the data can be viewed exactly how it resides in the knowledge graph, i.e., interactive. The user can use the Knowledge Graph page in the QSO Portal to navigate nodes via links between notes, or the user can drill down into the details in other ways.

Figure 1: Quantum Metascience Initiative (History of Ontology at previous a QSO event, with timeline) VIDEO 1 (https://youtu.be/60a7wwoRywU).

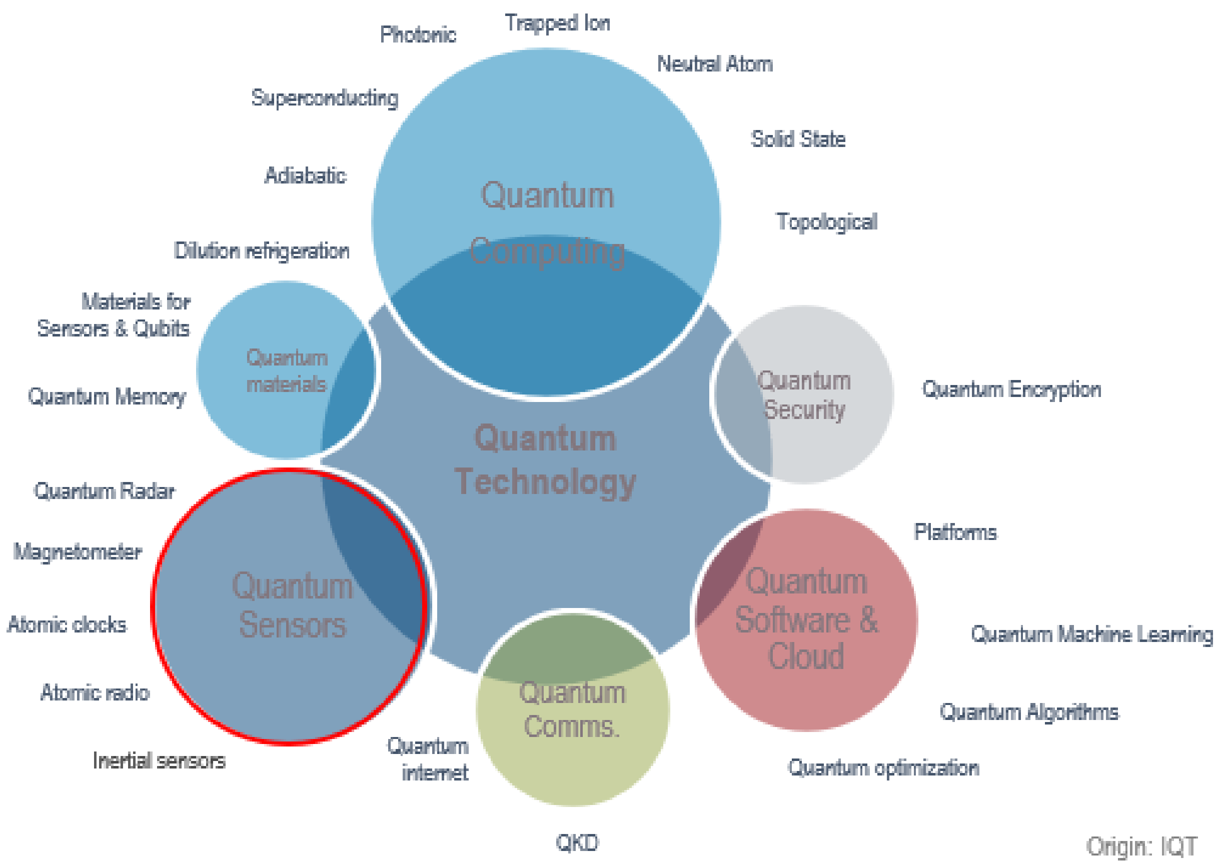

Figure 2: Quantum disciplines (modified from an original In-Q-Tel diagram).

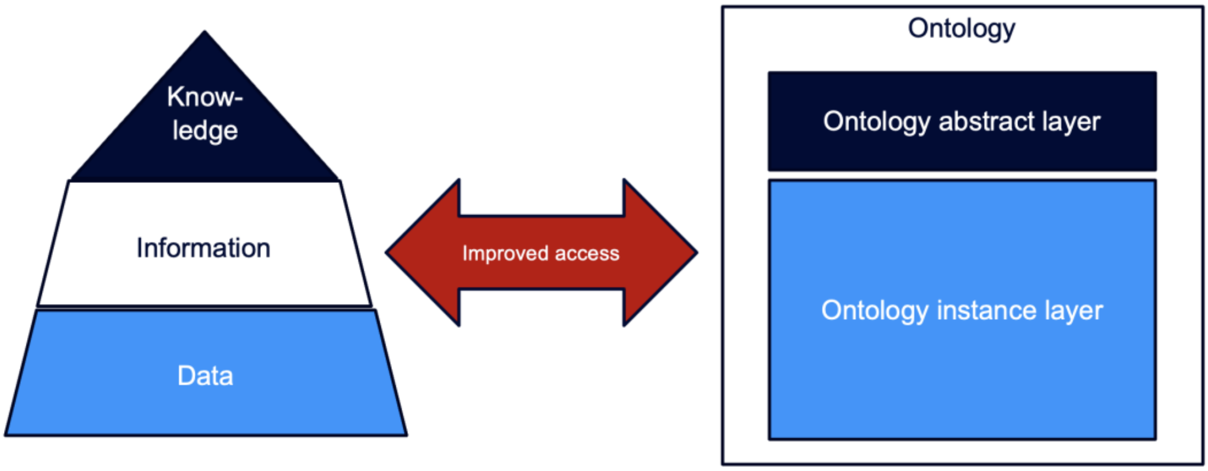

Figure 3: Ontology relationships (relationship of data, information and knowledge and their ontological representation).

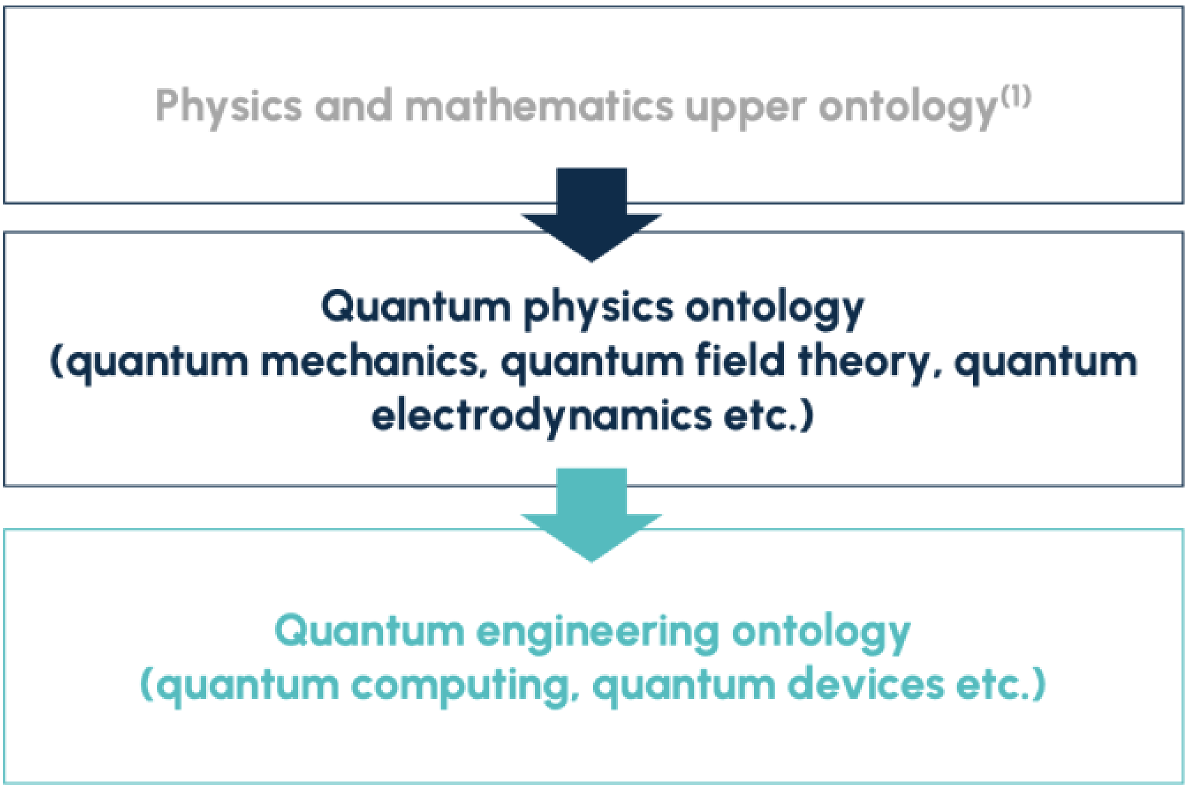

Figure 4: Relationships between physics and mathematics (relationship between physics and mathematics upper ontology, quantum physics ontology and quantum engineering ontology. *Upper ontologies out of scope of the QMI project).

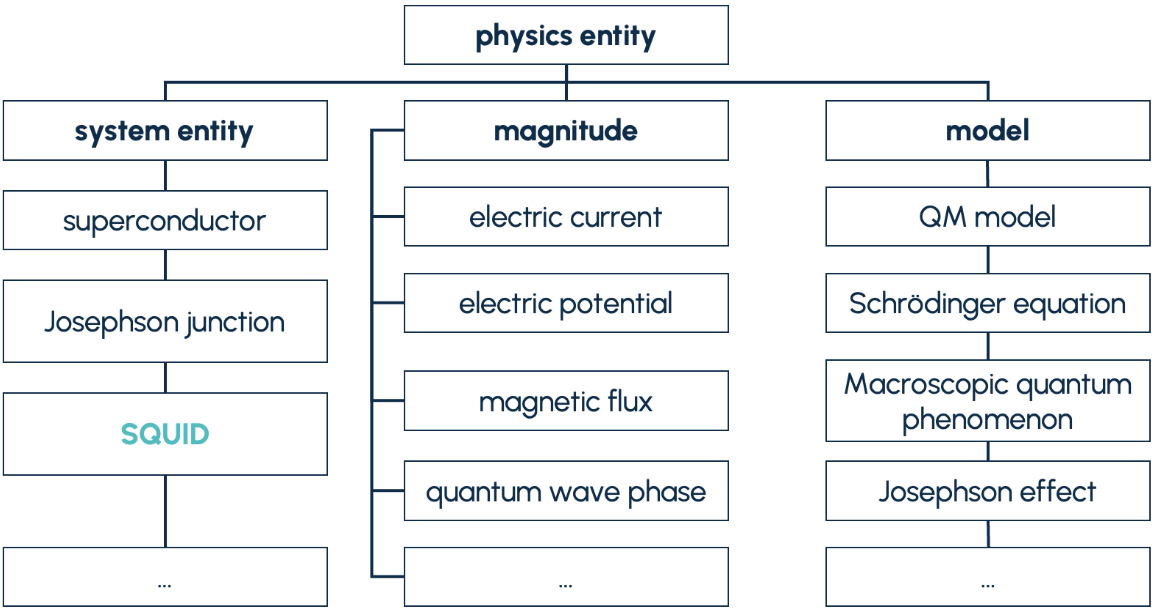

Figure 5: Superconducting quantum interference (a quantum device (the superconducting quantum interference device, SQUID, a quantum magneto-sensor) in incomplete ontological context (draft, illustrative).

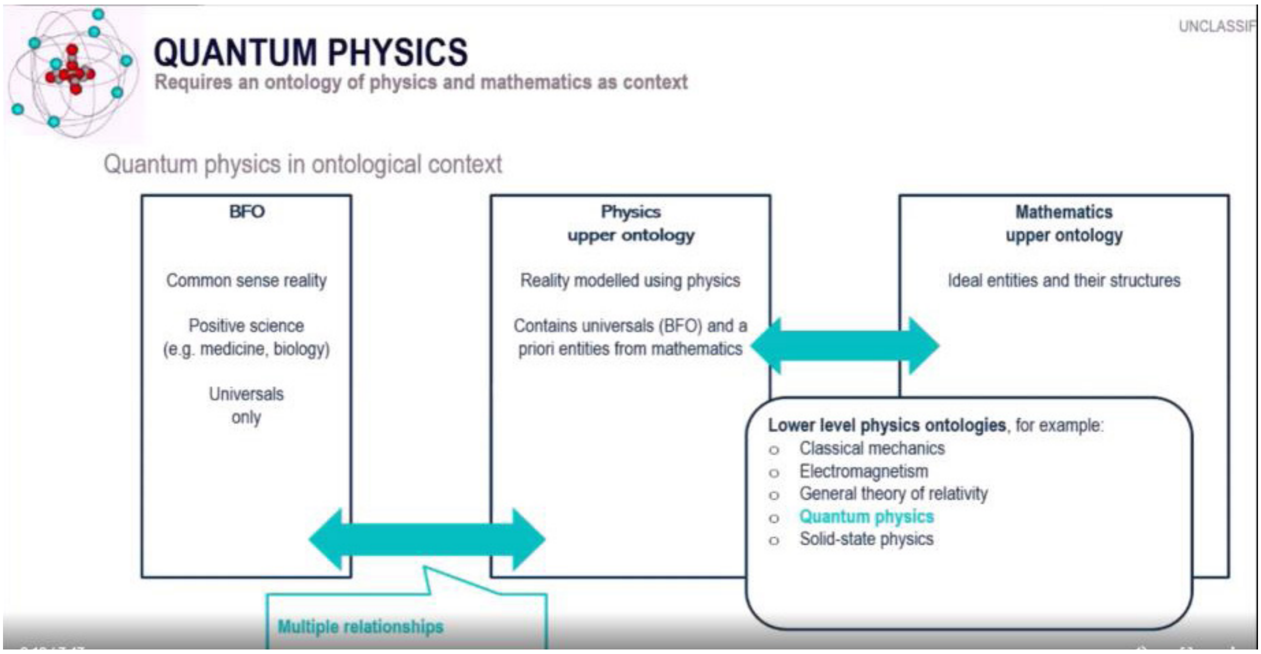

Figure 6: Quantum ontology content and structure (Dr. Jobst Landgrebe discusses quantum ontology content and structure. VIDEO 2 (https://youtu.be/1s4rNd8lu_g).

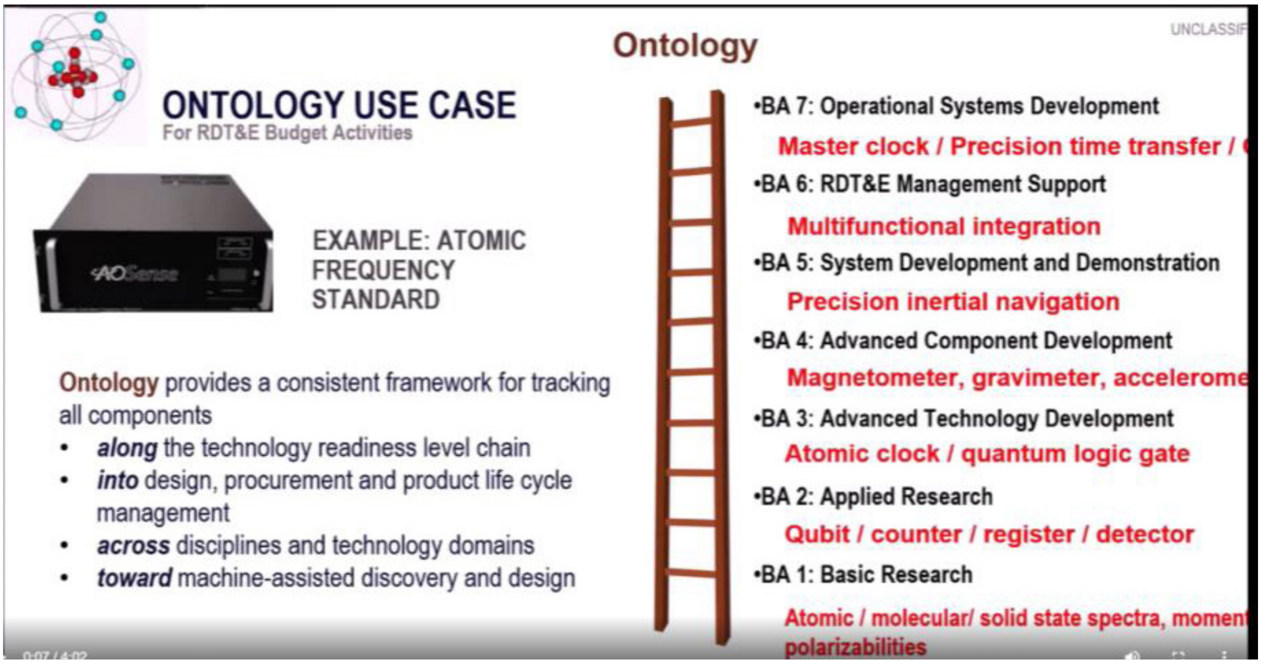

Figure 7: Quantum ontology use cases (Dr. Charles Clark discusses quantum ontology use cases). VIDEO 3 (https://youtu.be/Q66oJsrxVys).

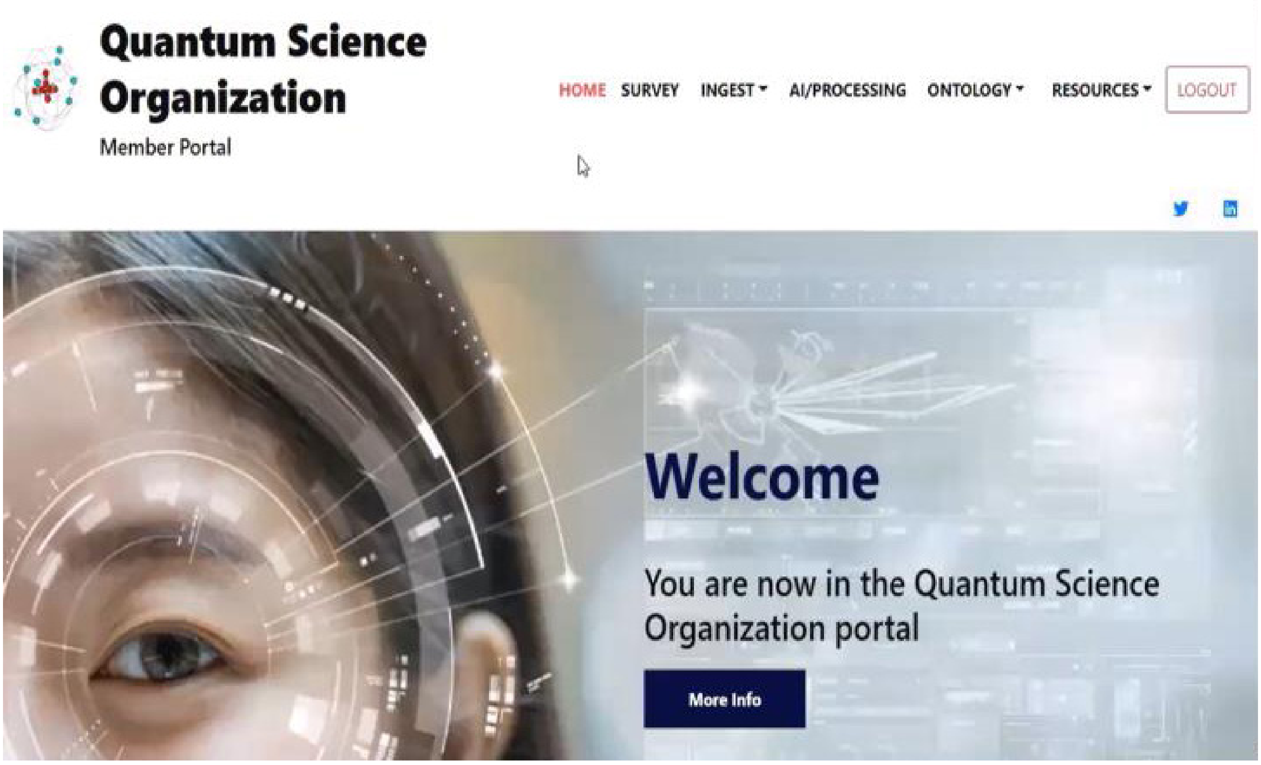

Figure 8: QMI Portal (Dr. Terry Jansen demonstrating and discussing the QMI Portal). VIDEO 4 (https://youtu.be/60a7wwoRywU).

Figure 9: University collaboration (NIU leading a panel discussion on QMI) VIDEO 5 (https://youtu.be/K6isNjRj0XE).

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