Formal Ontology in Information Systems
N. Aussenac-Gilles et al. (Eds.)

doi:10.3233/FAIA231135

Dental Restorative Material Ontology (DrMO)

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Abstract. The DrMO ontology is a domain ontology that represents knowledge underlying the composition, characterization and standardization of different materials involved in the dental restoration procedure. It will assist dentists in selecting appropriate materials based on up-to-date scientific knowledge to satisfy a patient's specific requirements, without jeopardizing their clinical time. It reuses several ontologies from the OBO foundry, especially the Oral Health and Disease (OHD) Ontology. However, the dental restoration domain is complex and also requires concepts from materials science and engineering. Thus, DrMO also incorporates knowledge from the Devices, Experimental scaffolds, and Biomaterials (DEB) and Functionally Graded Materials (FGM) ontologies to provide more comprehensive knowledge of this area of dental material than previous ontologies. However, much of the terminology from FGM is different than that used in clinical dentistry. Thus, DrMO has changed the appropriate classes to make them consistent with terminology common in dentistry. DrMO also follows ontology design best practices by reusing meta-data properties from the Dublin Core vocabulary. It captures knowledge from a set of the most recent and influential papers in Dental Materials and related fields. Links to these papers are included in the ontology as meta-data defined with Dublin Core. It is implemented in OWL2 and was developed with the Protégé 5.6 ontology editor. The ontology was created using the Ontology Development 101 methodology by Noy et. al. Several domain experts in addition to Dr. Dutta also provided their expertise. The ontology is available on GitHub and licensed via an open source license. The GitHub project includes a corresponding file of SPARQL queries that answer the competency questions defined as part of the ontology development methodology.

Keywords. Dental Restoration Material, Clinical Decision Support System, Oral Health, Dentistry, Ontology, Basic Formal Ontology, Web Ontology Language, SPARQL, Knowledge Graph

1. Introduction

Dentistry, a branch of clinical science, deals with the subject 'materials science' in conjunction with clinical subjects. The dental restorative procedure is a major part of dental treatment procedures. The goal of restorative procedures is to repair the function

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and aesthetics of missing teeth or surrounding structures. Materials utilized for tooth restoration procedures include different metals and their alloys, composite materials, cements, and ceramics. Each branch of dental materials has undergone an explosive evolution in the last few decades [1].

Teeth have a harmonized system with enamel, dentin, pulp and periodontal tissue with complete biocompatibility, sufficient bond strength, natural appearance, and tissue repair capability. The ideal restorative material with perfect simulation of these properties has not yet been invented. Thus, emergence of new material is still a continuous and complex process of trade-offs driven by the requirements for each individual patient. In addition, old materials may still be the best choice for some clinical conditions because of their time-tested efficacy, wide availability, technical simplicity, and cost effectiveness.

Dental Clinicians learn the subject of dental materials in their graduate syllabus mostly from different textbooks [2,3]. Up-to date information about those materials are available in the form of systemic reviews, field studies, and articles published in different data bases. Practically, the huge volume of the fast-growing dental material science and its dissemination among dental, medical, engineering and even physics and chemistry knowledge bases is nearly impossible to grasp by the dentist. There is very limited scope to capture and reuse the scattered knowledge in dental clinics. The clinician needs to choose the appropriate material for his/her patient on the first visit after recording the patients' signs, symptoms and performing intraoral and extraoral examination. Most of the time, the dentist has to rely on their accumulated knowledge and experience for a suitable material selection. Sometimes they have to depend on the manufacturer's marketing materials, which may be significantly biased.

An automated decision support system is a valuable tool for the dentist to keep them well informed with up-to-date knowledge. Different formats and heterogenicity of available knowledge of dental material is the prime obstacle. An ontology has the capability to play a crucial role to achieve interoperability among different data bases for a smart decision support system.

The present work is a formal representation of the dental material domain, more specifically the dental restorative material domain. The dental restorative material ontology (DrMO) represents the knowledge underlying the material selection process by the dentist for various dental restoration procedures. It supports finding the recommended manufactured object indicated for a particular dental restoration procedure along with the associated scientific evidence base. It captures currently available huge varieties of manufactured objects in the field of dental restorative material. In addition, it addresses all those materials' processing and manipulation, as well as part, properties, composition, and underlying active biological substances.

2. Relation to Previous Work

The DrMO ontology builds on and extends the Oral Health and Disease Ontology (OHD) [4] that is part of the OBO foundry of ontologies for biology and medicine. We are in the process of working with OHD developers to modify DrMO to be consistent with OBO.

OHD contains terms for representing dental anatomical structure, dental diseases (caries), dental procedures including dental restoration procedures, and dental restoration material. The purpose of DrMO is to support Clinical Decision Support Systems (CDSS) and to be used in the material selection process of dental clinics.

We have reused the *Tooth Restoration Procedure*[2] and terms related with health care processes from OHD. The superclass of tooth restoration procedure of DrMO is identical to that of OHD. However, there are some differences in OHD *Tooth Restoration Procedure's* subclasses.

OHD classifies tooth restoration procedures in six subclasses: *Direct Restoration Procedure*, *Indirect Restoration Procedure*, *Crown Restoration Procedure*, *Veneer Restoration Procedure*, *Intracoronal Restoration Procedure*, *Partial Denture Restoration Procedure*. In DrMO, the tooth restoration procedure is classified in three direct subclasses: *Direct Restoration Procedure, Indirect Restoration Procedure* and *Semi-direct Restoration Procedure* (a new class in DrMO). *Crown*, *Veneer* and *Intracoronal Restoration* are the subclasses of *Direct* and *Indirect Restoration Procedure* in DrMO, not siblings as in OHD.

The definition of necessary and sufficient conditions for classes is a way to support consistency and computational reasoning [5]. The definition of several axioms in DrMO builds on the definitions in OHD. E.g., in DrMO the definition for *Tooth Restoration Procedure* is "A dental procedure in which either a whole tooth or a part of a tooth is replaced by dental restoration material in order to reestablish the tooth's anatomical and functional form and function." However, the definition of some terms in DrMO differs from those in OHD. The OHD definition of *Veneer Restoration Procedure* is: "A tooth restoration procedure in which a thin layer of material (i.e., a veneer) is placed over one or more surfaces of the tooth either to improve the aesthetics of the tooth or to protect the tooth's surface from damage." There is no clear mention of the technique in the OHD definition, whether it is indirect or indirect. Following the Aristotelian definition structure (recommended by BFO, the upper level ontology of OHD), ensures that the veneer restoration procedure inherits the property of its superclass *Tooth Restoration Procedure* 'to reestablish the tooth's anatomical and functional form and function'. Then there is no added advantage of the mention of 'to improve the aesthetics of the tooth or to protect the tooth's surface from damage' in veneer restoration procedure's definition. In addition, With the advent of high strength composites present veneer restoration follows both direct and indirect techniques, whereas previously the common trend was to follow indirect techniques for veneers [6]. This distinction is missing from OHD but is made explicit in DrMO. In DrMO we separate Veneer Restoration into two different classes, one under Direct and one under Indirect restoration. For the same reason the other two sibling classes which are *Crown Restoration Procedure* and *Intracoronal Restoration Procedure* are the subclasses of direct and indirect tooth restoration procedure in DrMO, not the sibling as in OHD. This fact has been validated through literature review and interviewing practicing dentists [7]. The focus of OHD is broader in the field of dental treatments and it encompasses entities other than tooth restoration procedures. Whereas DrMO covers tooth restoration procedures at a finer level of granularity. Figure 1 and Figure 2, screen shots from the Protégé 5.6 ontology editor from DrMO and the OHD ontology respectively, illustrate the class hierarchy of *Tooth Restoration Procedure* in the different ontologies.

[2] Names of entities in the ontology will be shown in *italics*. Classes have every word in the name capitalized and properties have the first word in lower case and subsequent words in upper case.

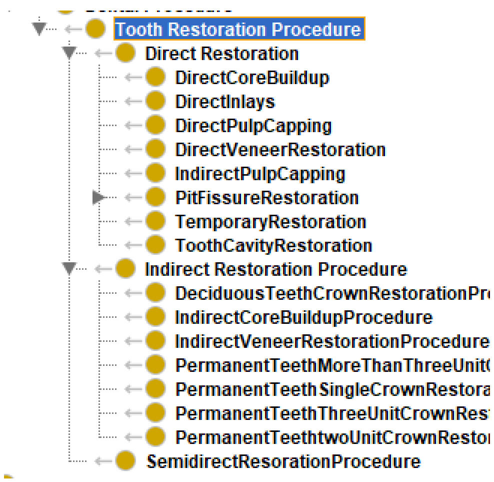

Figure 1. DrMO Tooth Restoration procedure and subclass (Protégé Screen shot)

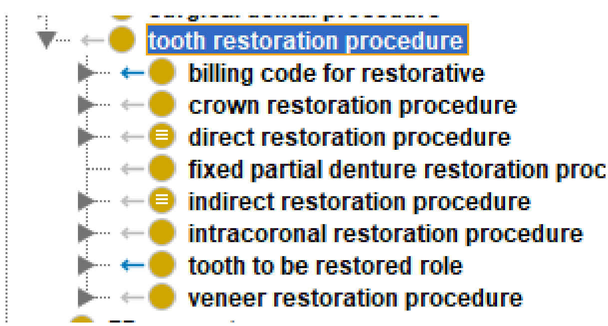

Figure 2. OHD Tooth Restoration procedure and subclass (Protégé Screen shot).

OHD models dental restoration material at a more abstract level because restoration materials were not their focus. DrMO builds on and adds additional detail to the OHD axioms that are required for a true understanding of this aspect of the dentistry domain. OHD's *Dental Restoration Material* is a processed material that bears a dental restoration material role. It has subclasses such as *Amalgam Dental Restoration Material* and *Resin Rental Restoration Material*. The dental restoration process requires dental restoration material as a core component. In addition, a supporting component of dental restoration is the requirement for liners and bases or pulp-protective agents in some clinical situations. Some resin dental material may act as bases (flowable resin) only below the actual restoration. Thus, if we categorize resin as a restorative material from the beginning it may create confusion. Hence, we use the class dental material from the NCI Thesaurus OBO Edition. In addition, we include metals, metal alloys such as amalgam, resin composite, and cements as subclasses of dental material. Different restoration procedures will require different dental materials. E.g., a composite resin may be used in the procedure of a dental restoration procedure or may be used as a base only under a restoration in some deep cavities.

DrMO's dental restoration material object *has Ingredient Dental Material*. This allows us to distinctly describe the application and ingredient (Composition) parts of dental materials in detail. This is similar to patterns followed in the Devices, Experimental scaffolds, and Biomaterials ontology (DEB) [8] and Functionally Graded Materials (FGM) ontology [9]. This representation will help to integrate the huge knowledge base of materials science with relevant knowledge from the Oral Health and Disease domain. There is a detailed description in the later part of the related work regarding the use of the class *Dental Restoration Material Object*.

An appropriate material selection for the dental restoration procedure demands knowledge of material properties such as strength, hardness, corrosion property, and wear resistance. The manufacturing ontology for functionally graded material (FGM) has a formal representation related to FGM, which is a subclass of composite materials. It has entities such as material corrosion resistance, strength, hardness, wear resistance and other relevant properties. FGM has several medical applications such as bone implant, and dental implant. DrMO has imported these properties from FGM. However, the term FGM is not very common in clinical dentistry. The dental material's classification pattern described in textbooks of dentistry is not similar with the classification of the FGM ontology. There are important properties of dental materials defined in DrMO. E.g., named aesthetic property, anticariogenic property, and several others which are beyond the scope of the FGM ontology.

In practice, dental materials are used as *Dental Material Object*, which is a subclass of *Manufactured Object*. The Devices, Experimental scaffolds, and Biomaterials Ontology (DEB) is a formal representation of *Manufactured Object* used for biological and medical applications. The DEB ontology has a very brief mention of dental materials because their main focus is "surgery, tissue engineering, cell-expansion, drug delivery and antimicrobial products". The class *Manufactured Object*, *Biologically Active Substances*, *Material Processing*, and a few other relevant terms have been reused from the DEB ontology.

DrMO covers entities important from both the Biological and Engineering domains. Composition based classification is common for engineering materials discussion because composition is an important guiding factor of a material's property [10]. Whereas, human anatomy, physiological process, oral environment diseases both systemic and dental diseases are important aspects for any material to be used in the human body (OHD, OGMS. OBI DEV). We have also reused classes from the NCI Thesaurus OBO Edition (NCIT).

The ontology covers all the materials' processing and manipulation part, properties, composition and underlying active biological substances.

DrMO represents dental restoration material objects, more specifically direct dental restoration material objects which are very commonly used in day to day clinical practice. "The global dental fillings market size was valued at USD 5.2 billion in 2018 and is expected to grow at a compound annual growth rate (CAGR) of 7.2% from 2019 to 2026" [11]. The dental filling material objects are only a subset of all direct dental restoration material objects. DrMO has the captures knowledge of indirect dental restoration material objects and dental prosthetic material objects.

3. Methodology

The ontology was created almost exclusively by Dr. Dutta who is a domain expert in dentistry but has no formal training in computer science or ontology development. Michael DeBellis provided guidance on specific technical issues such as the development of SPARQL queries, SWRL rules, and the distinction between IRIs and rdfs:labels. We utilized the methodology defined in Ontology Development 101 [12]. This methodology emphasizes defining basic domain concepts and scope first. The interview of domain experts results in the collection of competency questions to sketch the scope and granularity of the proposed ontology. These competency questions play the role that use cases play in the OMG Unified Modeling Language (UML) [13] and that stories play in Agile Methods [14]. They provide the vocabulary for classes (typically nouns in a competency question) and properties (typically verbs) for the ontology. In addition, domain knowledge from experts and knowledge from other relevant ontologies is integrated to the formal definition of the ontology.[3]

3.1 Ontology development

We initiated the ontology development process by gathering competency questions from interviews and questionnaire surveys among dental clinicians (presently only 5 dentists) and literatures related with the dental material selection process [15]

Competency questions:

1. Name a dental restorative material with high strength.
2. What ISO standardization is applicable for dental restoration material objects?
3. Which material should a dentist consider for the restoration of a patient with epilepsy?
4. Which dental restorative material is MRI safe?
5. Name a direct restorative material which is best for a mentally retarded patient.
6. Which restorative material is suitable for difficult access area of mouth?
7. Which restorative material is economical as well as durable?
8. Which one is the best restorative material both esthetically and functionally for anterior teeth?
9. Which material is suitable for a caries prone child with deciduous dentition?
10. Which material should a clinician consider for a young patient?
11. Which material should be appropriate for filling of class IV cavity with edge-to-edge bite.
12. Which material is the choice for a deep caries in a less equipped clinic of a village?
13. What journal article says about durability of different composite material?
14. What direct dental restorative material object has mercury as its ingredient?

3.2 Ontology Specification

The Dental Restoration Material Ontology (DrMO) contains relevant terms for the dental material selection process in clinics. In practice, clinicians use varieties of dental material objects, not the pure dental materials described in textbooks. Different manufacturers produce those manufactured objects by different trade names with different combinations of material ingredients. Manufactured objects in the field of dental restoration are the key concept of DrMO.

[3] Although Dr. Dutta is a domain expert, a weakness of the current project has been that we have not collected nearly enough feedback from independent domain experts.

There are several aspects already present for material selection. The question of suitable dental material selection should be based not only on the material's physical, chemical or mechanical properties, it must also be evaluated with respect to biocompatibility and safety of the material. There are already some international standards (the most accepted are the ISO standards). Dental Materials follows International Standardization for composition, safety and testing purposes. ISO TC 106 is responsible for standards for restorative, prosthetic materials and test methods. International Standardization for Dental Material is a concept of DrMO to strengthen the safety aspects of the material selection process. For a complete restoration process, along with the primary restorative materials, a few auxiliary dental materials play an important role and are concepts of DrMO:

- impression materials
- liners and bases
- adhesives luting agents

In textbooks tooth cavity follows Black's Classification. Recently ICDAS (International Caries Detection and Assessment System) classification is also utilized. However, in clinical practice restoration material selection does not depend only on theoretical classification. Rather, individual patient's requirements are also a critical deciding factor. For a class I posterior teeth cavity, some patients may need aesthetic restoration, some may select high stress restoration material for the same condition. Black's classification (Class I – Class V) are instances. Another patient specific variation is class V cavity of a rotated molar/premolar, which may face contact area stress and require high stress tolerable restoration (though usually class V restorations are non-stress bearing). The class *Dental Consideration* and its subclasses captured all those important aspects behind a material selection process.

Table 1 summarizes the DrMO specification in terms of scope, implementation language, target user and intended use required for the construct of a decision support system's knowledge base [16].

Table 1. DrMO specification in terms of domain, scope, Implementation language, target user and intended use.

Specification	Details
Purpose	Purpose of the ontology is a formal representation of dental restoration material objects, their material ingredient, processing, manipulation, properties, underlying active biological substances responsible for a specific clinical consideration and their recommended participation in different tooth restoration processes.
Scope	An ontology to be used for the selection process of specific dental restorative material with the support of evidence from journals and other clinical sources
Implementation Language	Web Ontology Language 2.0, Semantic Web Rule Language (SWRL), SPARQL 1.1 Query Language, OWLViz Plugin for Protégé, AllegroGraph Gruff visualization tool
Target user and Intended Use	i) **Dentists** for selecting appropriate materials based on up-to-date scientific knowledge to satisfy a patient's specific requirements. ii) **Manufacturers** of dental material objects for structuring their material description brochures in a both human readable and machine understandable format. iii) **Research scholars** from different communities, other than dentistry also to co-relate materials property with its composition, indication and contraindication.

3.3 Ontology development

The domain and scope determination guides the terms included in the ontology. The next step is to search and reuse domain ontologies, especially from the OBO foundry, as well as technical properties such as meta-data from Dublin Core.

Table 2 describes few of the reused ontologies and their domain. We have imported terms from clinical, dental as well as the materials science domain.

Table 2. List of reused Ontology from the OBO foundry in DrMO

Name of Ontology	Purpose	Domain
Oral health and Disease Ontology (OHD)	Structure, reuse and analysis of electronic dental health record data	Dental Disease
NCI Thesaurus OBO Edition (NCIT)	A reference terminology that includes cancer related diseases, findings and abnormalities.	Cancer domain
Devices, experimental scaffolds and biomaterials Ontology (DEB)	Identification, extraction and cataloguing of features of experimental scaffold and commercial implants.	Biomaterial
Ontology for general medical science (OGMS)	Entities involved in a clinical encounter	Medicine
Functionally graded material Ontology	It is a formal representation of one subclass of composite material named functionally graded material (FGM).	Material science
Modal Relation Ontology (MRO)	Mid-level Ontology	Relation
Information Artifact Ontology (IAO)	Mid-level Ontology represents types and provenance of information	Information

3.4 Ontology overview:

This section provides an overview of some of the most important classes and properties in the ontology. Figure 3 shows the object properties (the nodes in purple) that have *Dental Material Object* as their domain (indicated by blue lines) as well as the classes (green nodes) that have those properties as their range. Figure 4 shows properties (nodes in turquoise) that have *Manufactured Object* as their Domain or Range. The domain classes are the target of grey links and the range classes are targets of blue links.

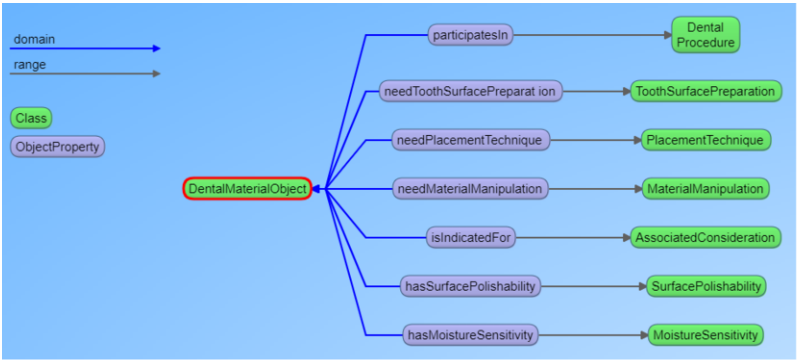

Figure 3. Properties with *Dental Material Object* as their Domain

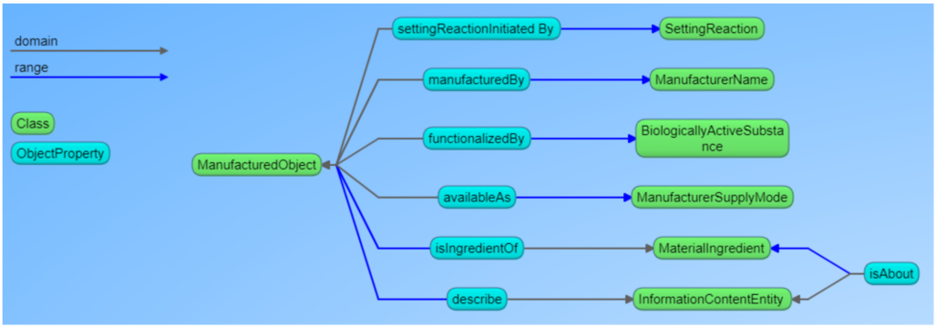

Figure 4. Properties With *Manufactured Object* as their Domain and Range

Table 3: Summery of few object property used in the ontology to define relationship between classes.

Object Property	Domain	Range	Inverse property
availableAs	Manufactured Object	Manufacturer Supply Mode	is AvailableFor
describe	Information Content Entity	Manufactured Object	describedBy
isAbout	Information Content Entity	Material Ingredient	isSubjectOf
participatesIn	Dental Procedure	Dental Material Object	hasParticipants
isIndicatedFor	Dental Material Object	Associated Consideration	hasIndication
isIngredientOf	Material Ingredient	Manufactured Object	hasIngredient
availableAs	Manufactured Object	Manufacturer Supply Mode	is AvailableFor

3.5 Formal Axioms and Rules

The fundamental capability of OWL that distinguishes it from previous Frame and Database languages available for wide-spread use with large systems and data is that OWL has a formal semantics that is a decidable subset of First Order Logic called Description Logic. Description logic has a long history tracing back to work in database theory and R&D languages such as NIKL and Loom [17]. These languages always showed great promise for reasoning and applications such as intelligent user interfaces [18]. However, before OWL, there was no standard that enabled systems which could scale to the terabytes of data required for modern IT systems. The standardization of OWL by the W3C provided a standard that vendors and researchers could utilize to develop tools capable of scale and integration with large conventional Information Technology systems. OWL's formal semantics enables the development of powerful reasoners that can automate a great deal of the logic that in the past had to be implemented in programs. This enables the formalization and capture of knowledge that in the past would be buried in code, documents, and the heads of experts. Two of the most powerful OWL features that take advantage of OWL's formal semantics are restrictions on classes and rules defined in the Semantic Web Rule Language (SWRL). The following example illustrates how DrMO utilizes these features.

We begin with the third competency question from section 3.1: What material should a dentist consider for a patient with epilepsy? To define dental patients with epilepsy we create a subclass of the *Human Dental Patient* from OHD called *Epileptic Dental Patient*. This is a defined OWL class, i.e., a class such that the axioms defined are both necessary and sufficient to recognize an instance of the class. The axiom is fairly simple: *Human Dental Patient and hasAssociatedCondition value Epilepsy*. Then we add a SWRL rule that captures the knowledge of our dental experts that an epileptic patient requires dental materials that have a less complex placement technique. This can be captured by the SWRL rule:

EpilepticDentalPatient(?p), needPlacementTechnique(?do, ?pt), LessComplexTechnique(?pt) -> suitableDentalMaterial(?p, ?do)

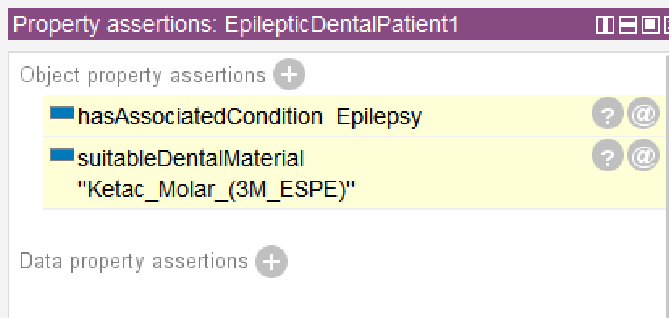

Figure 5. Values Asserted by the Reasoner based on Axioms and Rules

To meet the requirement for explanations discussed below, all reasoner inferences can be queried and a trace from the reasoner will provide an intuitive sequence of the axioms and rules that resulted in the inference. In the current version of DrMO there is only a small amount of test data, in this case, one instance of the class *EpilepticDentalPatient* called *EpilepticDentalPatient1*. The reasoner asserts two values for this individual. First, using the axioms that define the class it asserts that the individual has the associated condition *Epilepsy*. Second, using the SWRL rule it asserts that the suitable dental material for the patient is *Ketac_Molar_(3M_ESPE)* because it is the only material in the ontology at this point that has a less complex placement technique.

3.6 Ontology Application

The intended application of DrMO is to support finding manufactured objects indicated for a particular dental restoration procedure along with the associated scientific evidence base. In addition, DrMO is being harmonized with the OBO OHD ontology and incorporated into the OBO repository to extend the coverage of OBO to dental materials in more depth.

Clinicians require real-time access to integrated data as and when they require it. There is enthusiasm among bioinformatic researchers for clinical decision support systems (CDSS). Existing technology, its tools, and its ease of access, including open-source options, can manage disseminated health data. However, acceptance of those tools among clinicians is a cause of disappointment in the bioinformatician community [19]. Our long term goal is to make the knowledge in DrMO widely available to practitioners via the creation of an intuitive GUI that builds a CDSS with DrMO and the ontologies it reuses such as the CDSS knowledge base. Previous researchers have determined barriers to the acceptance of such technology [20]. The most critical issue is understandability. It is not sufficient to simply provide an answer. Experts require that an explanation of the reasoning behind the answer is also available and understandable, i.e., "black boxes are unacceptable". This is one of the primary advantages of the semantic approach to AI over Machine Learning. Machine Learning systems are typically black boxes where the reasoning is buried in nodes in a graph or variables in complex algorithms that domain experts (and often even the developers of the ML systems) can't understand. User experience experts advocate delivery of domain knowledge with a deep understanding of the domain which will lead to the relevant terms for the domain defined in formalisms such as is-a hierarchies and rules that are intuitive to domain experts. DrMO tried to maintain those principals with an output of both precise and explicit representation of the dental restoration material domain. The goal is not to replace the expertise of clinicians, but rather to enhance it by providing relevant knowledge that may not be easily obtainable.

Along with clinical expertise and patient priority, there is a requirement to search the up-to-date, relevant evidence. Figure 6 below describes the conventional model of evidence searching, which is time consuming and complex.

The long term goal of DrMO is to support the search process through a CDSS which will be both efficient and fast in comparison with the conventional model described in Figure 6. Search that is enhanced due to the use of an ontology is known as Semantic Search. Semantic search is superior to conventional search because:

- It can take advantage of the reasoner and the ontology to enable searches that are intuitive and let domain experts interact with the knowledge graph in domain rather than technical terms [18].
- The SPARQL query language is very flexible and enables search on any or all parts of triples in the knowledge graph.

- Graph databases are typically faster than relational databases for complex knowledge because they don't require complex table joins as relational databases do.
- Linked Data [21] can further supplement searches with information from large repositories of information such as DBpedia.[4]

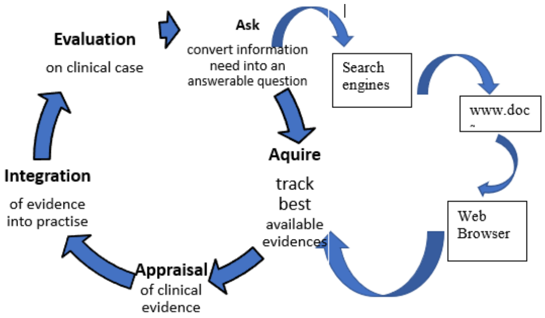

Figure: 6. Five-step sequential model to search evidence (adapted from Sacket et al. 2011) with commonly practiced evidence searching procedure.

3.7 Public Access

DrMO is available to the public via a Creative Commons open source license on Github at: https://github.com/Nivedita79/DrMO. The repository also includes a separate file of SPARQL queries that address many of the competency questions. Competency questions not addressed by SPARQL are implemented as SWRL rules.

4 Discussion

DrMO extends the OBO Oral Hygiene and Dentistry ontology with knowledge about the domain of dental materials for restorative processes. This is a complex domain because in addition to concepts from dentistry, biology, and medicine it also requires knowledge from materials science which is itself an interdisciplinary field weaving together concepts from engineering, manufacturing, chemistry, and physics. The ontology reuses many different ontologies from these various domains as well as adding additional concepts based on expertise from interviewed domain experts and papers from leading journals and conferences. The next important step for the ontology is to work with members of the OBO community to make the ontology conform to the OBO standards and have it included in the OBO repository. We have begun this process already via discussions with members of the OBO community, especially the developers of the OHD ontology.

A common complaint voiced by Information Technology (IT) practitioners against formal domain models is that such models require too much academic knowledge and are not appropriate for the everyday domains that most business and professional people

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[4] Dbpedia.org

work with [22]. This has resulted in a hodge podge of various ad-hoc informal models (often called Taxonomies) that have no semantics, integrate concepts such as is-a and part-of and are hence open to various interpretations by each individual [5]. Such informal models are difficult to maintain, extend, and utilize. DrMO shows the fallacy of such arguments. The lead designer (Dr. Dutta) had no formal training in Semantic Web languages such as OWL, let alone logic or set theory, yet she was able to develop a model that built on several existing domain ontologies and extended them with significant detail regarding tooth restoration, a process that requires a heterogenous combination of knowledge such as clinical dentistry and materials science. She was able to accomplish this due to the intuitive user interface of the Protégé ontology editor and the fact that far from requiring a PhD in logic, languages such as OWL tap into concepts that humans use every day to categorize their knowledge even though they are usually unaware of it [23].

In the modern world of Information Technology data has transitioned from a byproduct that supports the running of the enterprise to one of the, if not the most valuable assets of the enterprise, as valuable as factories, computers, and other critical infrastructure. Formal languages such as OWL provide the needed rigor and semantics to be unambiguous, understandable, and interpretable both by machines and humans. Unlike taxonomies which are primarily designed for human use and when utilized by software embed the semantics of the model in code, ontologies explicitly represent the semantics in a formal model that can be understood by both machines and humans. As DrMO demonstrates such formal models can be developed and used by domain experts with minimal training and will provide competitive advantage to corporations that adopt them as a way to model their data and capture critical knowledge about their business. They also provide a tool for experts to capture valuable knowledge in a form that can be reused both by machines and humans and will help bring critical care to underserved populations in healthcare and other critical human needs.

Acknowledgements

This work was conducted using the Protégé resource, which is supported by grant GM10331601 from the National Institute of General Medical Sciences of the United States National Institutes of Health. Thanks to Franz Inc. (http://www.allegrograph.com) for help with the Gruff visualization tool. Also want to acknowledge Professor Deepak Khemani, S.Baskaran for providing an insight on knowledge representation and reasoning through their course conducted by (onlinecourses.nptel.ac.in/noc22_cs02) National Programme on Technology Enhanced Learning (NPTEL) and Dr Biswanath Dutta (ISI, Bangalore, India) for the motivation to initiate the DrMO project. Thanks to Bill Duncan and the entire OHD team for their invaluable assistance in understanding and adopting OBO standards.

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