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Semantic Interoperability

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Abstract
This entry discusses the importance of semantic interoperability in the networked environment, introduces various approaches contributing to semantic interoperability, and summarizes different methodologies used in current projects that are focused on achieving semantic interoperability. It is intended to inform readers about the fundamentals and mechanisms that have been experimented with, or implemented, that strive to ensure and achieve semantic interoperability in the current networked environment.

INTRODUCTION

Semantic interoperability, which is defined as the ability of different agents, services, and applications to communicate (in the form of transfer, exchange, transformation, mediation, migration, integration, etc.) data, information, and knowledge—while ensuring accuracy and preserving the meaning of that same data, information, and knowledge—is central to the effective management, sharing, and retrieval of information in an open environment. Within the spectrum of different perspectives on interoperability, semantic interoperability lies at the heart of all matters. It deals with the language and vocabulary used in communication (human and machine) and facilitates information retrieval and resource sharing by users through whatever language or vocabulary they choose to use (often across language and cultural barriers). This entry is intended to inform readers about the fundamentals and mechanisms that have been experimented upon, or implemented, that strive to ensure and achieve semantic interoperability in the current networked environment.

Related standards such as the Resource Description Framework (RDF),[1] RDF Schema,[2] Web Ontology Language (OWL),[3] and Simple Knowledge Organization Systems (SKOS),[4] developed under the auspices of the World Wide Web Consortium (W3C), and the theoretical basis of semantics, are not discussed in detail here; these topics are covered in separate entries elsewhere.

SEMANTIC CONFLICTS AND AGREEMENTS

The ability to exchange services and data with and among components of large-scale distributed systems is contingent on agreements between requesters and providers. Those agreements may be based on e.g., message-passing protocols, procedure names, error codes, and argument types. This means that these exchanges must make sense—that the requester and the provider have a common understanding of the meanings of the requested services and data.[5] When multiple pieces of information are being exchanged, however, correct interpretation of some or all fractions of that information may be considered either partially or perfectly interoperable semantically.

We shall consider the example of the sequence "071210," which can be literally transferred from one system to another; however, its meaning may be interpreted in any number of different ways. We might ask:

1. Is it a string or an integer?
2. If it is a string, does it represent a date, a phone number, an area code, or a hexadecimal number representing a color?
3. If it specifies a date, what date is it: a person's birth date, a publication's issuing date, or an archaeological site's discovery date?
4. If it represents a date associated with a historical monument, what date is it indicating: the creation date, the restoration date, or the alteration date?
5. If "071210" represents a date in the twentieth century, which format does it represent: yy-mm-dd (i.e., 1907, December 10), mm-dd-yy (i.e., July 12, 1910), mm-yy-dd (i.e., July 1912, 10), or dd-mm-yy (i.e., 07 December, 1910)?
6. If information about *start-time* and *duration* is provided in a system, will the values be equal to the *earliest-date* and *latest-date* (derived by adding duration to the start-time) that are modeled on another system?
7. If "1912" is the value of a year in a system, how could this be mapped to the terms representing the same time period but from different perspectives?

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For example, in a Dublin Core (DC) record, this value associated with *dc.coverage* could be "Republic of China 1st Year (民国元年),"[6] or in a MAchine-Readable Cataloging (MARC) record, in field 260, it could appear as "min kuo 1 [1912]."
8. If the value of the year "1912" from one system is to be mapped to a value defined by another system, how should the non-one-to-one correlation be reconciled? For example, when applying the Library of Congress Subject Headings (LCSH) in subject-related fields in many metadata records, the closest match to "1912" might be a longer time period (e.g., "Nineteen Tens"), especially in the context of historical events, e.g., "Qing dynasty, 1644–1912" or "United States—History—1865–1921."
9. If a system was designed to generate a second value from a value, e.g., "date < 1920," which should result in the corresponding value "class = unclassified" (in terms of document release status), will another system be able to interpret the aggregated value?

Indeed, the number could represent almost any of millions of types of quantitative measure, and the strings could be mapped to constructed expressions in many different systems. Questions such as those above illustrate just some of the many possible *semantic conflicts*.

Interpretation of the meanings carried by the string depends strictly on the circumstances of transmission according to the *agreements* among systems. One study[7] states that the goal of interoperability is to build coherent services for users from components that are technically different and managed by different organizations. This requires cooperative agreements at three levels:

- Technical agreements cover, among other things: formats, protocols, and security systems so that messages can be exchanged.
- Content agreements cover data and metadata and include semantic agreements on the interpretation of information.
- Organizational agreements cover group rules for access, preservation of collections and services, payment, authentication, and so on.

Semantic agreements require the involvement of people (users, designers, and developers) who associate semantics with data structure, data content, and data values. The impact could be at any of the implementation levels such as procedure names, type definitions and type hierarchies, screen layouts, and report formats (e.g., titles, column and row headings, dates, units of measures, sort order, or footnotes). These and many other types of semantic information might be *implicit* in application codes, in diagrams, and in the local "oral tradition."[5]

Experience has shown that interoperability through comprehensive standardization is hard to achieve.[7] There is a need to maximize the amount of semantics that can be utilized and to make it increasingly *explicit*.[8] Making semantics explicit in metadata would allow people to detect mismatched assumptions and to create the required mappings to overcome them, despite the still extraordinary difficulties.[5]

DIMENSIONS OF INTEROPERABILITY

There have been many attempts at defining the concept of *interoperability*. Stressing a result-oriented definition, *Understanding Metadata* states that "[i]nteroperability is the ability of multiple systems with different hardware and software platforms, data structures, and interfaces to exchange data with minimal loss of content and functionality."[9] Other groups emphasize a process-oriented definition: "Interoperability is the ability of two or more systems or components to exchange information and use the exchanged information without special effort on either system"[10] "Interoperability: The compatibility of two or more systems such that they can exchange information and data and can use the exchanged information and data without any special manipulation."[11]

It should be apparent that merely having the ability of two or more systems or components to exchange data does not ensure correct interpretation of an integer or string. Interoperability issues must be addressed not only at the syntactic and functional levels, but also at the semantic level.[12] Without *syntactic interoperability*, data and information cannot be handled properly with regard to formats, encodings, properties, values, and data types; and therefore, they can neither be merged nor exchanged. Without *semantic interoperability*, the meaning of the language, terminology, and metadata values used cannot be negotiated or correctly understood.[13] Varying degrees of semantic expressivity can be matched with different levels of interoperability: low at syntactic interoperability, medium at structural interoperability, and high/very high at semantic interoperability.[14]

Ouksel and Sheth[15] identify four types of heterogeneity which correspond to four types of potential interoperability issues:

- System: incompatibilities between hardware and operating systems.
- Syntactic: differences in encodings and representation.
- Structural: variances in data models, data structures, and schemas.
- Semantic: inconsistencies in terminology and meanings.

Obrst,[14,16] on the other hand, intertwines six levels (object, component, application, system, enterprise, and community) of interoperability with three kinds of integration (syntactic, structural, and semantic). According to Obrst, semantics is fundamentally interpretation within a particular context and from a particular point of view. Semantic interoperability/integration is fundamentally driven by the communication of coherent purpose.

Pollock and Hodgson[17] consider data to be the foundation of all information sharing programs and believe that next-generation systems rest upon an expanded view of the dialectic of data—information. This view is illustrated in a pyramid in which the interface-level integration, method-level integration, and process-level integration all have developed on top of a foundation of data. With semantic interoperability, the expanded notion of data includes *semantics* and *context*, which thereby transforms data into information. This transition both broadens and deepens the foundation for all other integration approaches, blending semantic interoperability within various levels of interoperability:

1. Semantic interoperability of *data* enables data to maintain original meaning across multiple business contexts, data structures, and schema types.
2. Semantic interoperability of *process* enables specific business processes to be expressed in terms of another by: 1) inferring meaning from the process models and contextual metadata; and 2) applying it in a different process model elsewhere or outside the organization.
3. Semantic interoperability of *services/interface* enables a service to look up, bind, and meaningfully communicate with a new service.
4. Semantic interoperability of *applications* enables platform-independent interactions between heterogeneous software applications.
5. Semantic interoperability of *taxonomy* enables correct expression of all categories (including the definitions and relations with other categories) between different taxonomy systems.
6. Semantic interoperability of *policies and rules* enables businesses to protect valuable resources.
7. Semantic interoperability of *social networks* enables people in different communities of interest to network, make inferences, and discover meaningful connections.[17]

In general, interoperability, no matter at what level, is concerned with the capability of different information systems to communicate with one another. This communication may take various forms such as the transfer, exchange, transformation, mediation, migration, or integration of information. Therefore, as stated at the outset, we may define semantic interoperability as the capacity for different agents, services, and applications to communicate data, information, and knowledge while ensuring accuracy and preserving the meaning of that data, information, and knowledge.

PERSPECTIVES ON THE CONSTITUENTS OF SEMANTIC INTEROPERABILITY

Semantic interoperability has been a topic discussed in information processing and exchange communities since long before the World Wide Web emerged. However, the issue has never been so critical or of such great concern among so many communities as today. Although the Web is an information resource with virtually unlimited potential, this potential is relatively untapped because it is difficult for machines to process and integrate this information meaningfully.[18] Components that contribute to achieving semantic interoperability have been proposed by researchers from a number of diverse perspectives.

Semantic Interoperability in Different Processes

In a report entitled *Semantic Interoperability in Digital Library Systems* prepared by Patel, Koch, Doerr, and Tsinaraki at UKOLN, a research organization that is based at the University of Bath, U.K.,[19] semantic interoperability is characterized by the capability of different information systems to communicate information consistent with the intended meaning of the encoded information (as it is intended by the creators or maintainers of the information system). It involves: 1) the processing of the shared information so that it is consistent with the intended meaning; and 2) the encoding of queries and presentation of information so that it conforms to the intended meaning regardless of the source of information.

Seligman and Rosenthal[20] categorize information interoperability according to two principal types of processes. For information exchange, a provider responds to a request, and the information is transformed to suit the requester's needs. For information integration, in addition to being transformed, information from multiple sources is also correlated and fused. Integration requires that four levels be addressed: Level 1—Overcome geographic distribution and infrastructure heterogeneity; Level 2—Match semantically compatible attributes; Level 3—Mediate between diverse representations; Level 4—Merge instances from multiple sources. Information interoperability is required both in the information exchange and information transfer processes.

Obrst[14] has suggested that semantic interoperability could be enabled through: 1) establishing base semantic representation via ontologies (class level) and their knowledge bases (instance level); 2) defining semantic mappings and transformations among ontologies; and 3) defining algorithms that can determine semantic similarity by employing their output in a semantic mapping facility that uses ontologies.

In many cases, mapping and integration are conducted on top of existing systems that might have been created without considering integration with other systems. Addressing semantic interoperability in different processes helps to identify related problems and methodologies and then resolve those (and other) issues.

Semantic Interoperability at Different Levels

The UKOLN report on *Semantic Interoperability in Digital Library Systems* distinguishes three levels of information that are treated in a distinct manner to address semantic interoperability[19]: 1) *data structures*, be they metadata, content data, collection management data, or service description data; 2) *categorical data*—data that refer to universals, such as classification, typologies, and general subjects; and 3) *factual data*—data that refer to particulars, such as people, items, or places. It might be expected that the treatment of data structures and factual data would achieve a high level of semantic agreements; however, this correlation is not guaranteed when dealing with categorical data. Whereas the local degree of standardization of categorical data may be very high, the global one may be poor.

Slightly different from the perspectives above is a differentiation based on *data structure*, *data content*, *data values*, and *data communication* in metadata practices. The most notable practice is in the cultural heritage community, which has developed a set of comprehensive standards and guidelines for describing cultural objects. The conceptual reference model (CRM) produced by the International Committee for Documentation (CIDOC) of the International Council of Museums (ICOM) provides definitions and a formal structure for describing the implicit and explicit concepts and relationships used in cultural heritage documentation. Semantic interoperability is defined as the capability of different information systems to communicate information that is consistent with intended meaning (see also the "Semantic Interoperability in Different Processes" section). More precisely, the intended meaning encompasses: 1) the data structure elements involved; 2) the terminology appearing as data; and 3) the identifiers used in the data for factual items such as places, people, objects, etc.[21] In the museum and visual resources community, agreements have been reached on these constructs to ensure the creation of sharable and high-quality metadata. Categories for the Description of Works of Art (CDWA)[22] defines a *data structure* which "enumerates a set of categories or metadata elements that can be used to create a structure for a fielded format in a database."[23] Cataloging Cultural Objects (CCO)[23] is a *data content* standard that guides the choice of terms and defines the order, syntax, and form in which data values may be entered into a data structure. Examples of standards for *data values* in the form of controlled vocabularies include the Art and Architecture Thesaurus (AAT),[24] the Thesaurus for Graphic Materials (TGM),[25] the Union List of Artist Names (ULAN),[26] and the Getty Thesaurus of Geographic Names (TGN).[27] Data content and data value standards must be used in conjunction with an agreed-upon data structure.

Chung and Moen's two-dimensional approach for investigating issues of semantic interoperability in digital libraries[28] is related to the two perspectives above. The *data-attribute* area defines the names, labels, semantics, and granularity of metadata elements and database fields. The *data-value* area addresses the data or information provided in an element or database field. In this approach, the deduction that the data-attribute dimension's components are *semantics* and *content* was based on another discussion about metadata interoperability by the authors of this entry.[29] In that paper, the *semantics* aspect is understood to constrain the attributes (metadata elements and their refinements and relationships) according to agreed-upon meanings. The *content* aspect is defined as the declarations or instructions of what and how data values should be assigned to the metadata element.

Addressing semantic interoperability at different levels leads to improved standardization in related communities and the correct implementation of standards at each level. Following all agreements, metadata produced are intended to be shareable from day one.

Conceptualizing Underlying Models

As early as 1923, Ogden and Richard published their famous *triangle of meaning* which illustrates the relationship between language, thought content, and referent.[30] The graph implies that the referent of an expression (a word or another sign or symbol) is relative to different language users. The model was also adopted by researchers in library and information science as the basis for building knowledge organization systems (KOS).[31] A working group of the International Federation of Library Associations and Institutions (IFLA) Functional Requirements for Subject Authority Records (FRSAR)[32] has recently proposed a conceptual model that contains thema and nomen entities related to the *aboutness* of works in the bibliographic universe.[33] In this instance *thema* means anything that can be the subject of a work. *Nomen* is any alphanumeric, aural, and visual (etc.) symbol or combination of symbols by which a thema is known, referred to, or addressed. The importance of this model for the subject authority data is to separate and distinguish the concepts (or topics and subjects) from how they are designated or represented. In different efforts to achieve global sharing and use of subject authority data, some have focused on nomen (e.g., a translated metadata vocabulary, a symmetrical multilingual thesaurus, or a multi-access index to a vocabulary). However, the majority of projects have concentrated on the thema level, e.g., mapping the concepts between two thesauri or between a thesaurus and a taxonomy. These concept-centric efforts usually encounter far greater challenges because they are concerned not only with the concepts as such, but the relationships among them as well.

This thema–nomen conceptual model matches well with encoding languages such as SKOS, OWL, and more general encoding that uses RDF with Uniform Resource Identifiers (URIs) as the basis of a mechanism for identifying subjects, predicates, and objects in statements. SKOS defines classes and properties sufficient to represent the common features found in a standard thesaurus and is an example of the concept-centric view of vocabulary where primitive objects are not terms but abstract concepts represented by terms/labels. Each SKOS concept is defined as an RDF resource, and each concept can have RDF properties attached, which include: one or more preferred terms (at most one in each natural language); alternative terms or synonyms; and, definitions and notes with specification of their language.[34] Established semantic relationships are expressed in SKOS and intended to emphasize concepts rather than terms/labels.

When the DCMI Abstract Model[35] became a DCMI Recommendation in 2007, its one-to-one principle (i.e., each DC metadata description describes one, and only one, resource) was recognized or followed by more metadata standards (e.g., the newly released VRA Core 4.0).[36] Under the one-to-one principle, a record can contain more than one *description set*. A description set contain *descriptions* composed of *statements* which use property–value pairs. The results are data which can then be processed, exchanged, referred to, and linked to at the statement level. At implementation, when a record contains descriptions of the resource, the individual descriptions also can be linked to the authority data that manages the *values* associated with those properties (e.g., the subject authority data, the property name authority data, and the geographic authority data). Such an information model is independent of any particular encoding syntax and facilitates the development of better mappings and cross-syntax translations.[35] The conceptual model proposed by the FRSAR group corresponds to this abstract model because it allows any thema to be independent of any nomen, including any syntax that a nomen may use. This results in facilitating the sharing and reuse of subject authority data among not only the subject vocabularies themselves, but also among metadata resources.

SEMANTIC INTEROPERABILITY ACTIVITIES

The researchers at UKOLN (see the section "Semantic Interoperability in Different Processes")[19] proposed a list of the information life cycle activities in which the creators/authors, publishers, information systems managers, service providers, and end users are all involved. These activities include: 1) creation and modification; 2) publication; 3) acquisition, selection, storage, system and collection building; 4) cataloging (metadata, identification/naming, registration), indexing, knowledge organization, knowledge representation, and modeling; 5) integration, brokering, linking, syntactic and semantic interoperability engineering; 6) mediation (e.g., user interfaces, personalization, reference, recommendation, and transfer); 7) access, search, and discovery; 8) use, shared application/collaboration, scholarly communication, annotation, evaluation, reuse, and work environments; 9) maintenance; and 10) archiving and preservation. While semantic interoperability issues seem to be relevant in each part of the information life cycle, they are paramount in activities 4 (cataloging), 5 (integration), and 6 (access).

In this section, we will narrow our focus to the activities concerned with metadata and KOS because they are the two areas of most interoperability efforts. In reports on data exchange and integration, data values in metadata records appear to lead to increased scrutiny with regard to the semantics of semantic interoperability. This is because most of the concerns are related to terms or codes controlled by some form of KOS. It is our observation, however, that in addition to providing controlled terms, names, and codes for metadata value spaces, KOS have a more important function: to model the underlying semantic structure of a domain and to provide semantics, navigation, translation through labels, definitions, typing, relationships, and properties for concepts.[37,38]

KOS Interoperability

Knowledge organization systems have been recognized as the prerequisites to enhanced semantic interoperability.[19] The term KOS is intended to encompass all types of schemes for organizing information and promoting knowledge management, including classification schemes, gazetteers, lexical databases, taxonomies, thesauri, and ontologies.[39] Embodied as Web services, they facilitate resource discovery and retrieval by acting as semantic road maps, thereby making a common orientation possible for indexers and future users, either human or machine.[38] Thus the term KOS refers to controlled vocabularies as well as to systems/tools/services developed to organize knowledge and to present the organized interpretation of knowledge structures.

Establishing and improving semantic interoperability in the whole information life cycle always requires the use of KOS.[40] Sometimes new vocabularies need to be created (or extracted) first; in other cases, existing vocabularies need to be transformed, mapped, or merged.[19] This is especially important—and challenging—if existing KOS are different with regard to structure, domain, language, or granularity. In a project conducted by the authors,[41] over 40 KOS were found to have been involved in interoperability projects between 1980 and 2004. The sizes of differing KOS ranged from less than 100 to nearly one-quarter million terms depending on individual system requirements. Several of the projects comprise different vocabularies, ranging from a dozen, e.g., the Renardus project[42] and H.W. Wilson's combined heading list,[43] to over one hundred, e.g., the Unified Medical Language System (UMLS),[44] and many are multilingual. During the transforming, mapping, and merging of concept equivalencies, specific term representations formed with definite syntax are sought. Different types of equivalencies have been defined by various standards organizations. The complex requirements and processes for matching terms, which are often imprecise, may have a significant impact on the following aspects of vocabulary mapping: browsing structure, display, depth, nontopical classes, and the balance between consistency, accuracy, and usability. Various levels of mapping/linking can coexist in the same project, such as those identified by the Multilingual Access to Subjects (MACS) project:[45] terminological level (subject heading), semantic level (authority record), and syntactic level (application).[46]

Special challenges and controversial opinions have always overshadowed the projects that have attempted to map multilingual vocabularies. For example, equivalence correlation must be dealt with not only within each original language (intra-language equivalence), but also among the different languages (inter-language equivalence) involved. Intra-language homonymy and inter-language homonymy are also problematic semantic issues.[47]

Taking a different view, Gilreath[48] suggests that there are four basic requirements that must be harmonized in terminology work: concepts, concept systems, definitions, and terms. Further complications arise when perspectives of different cultures need to be integrated. With the assumption that all languages are equal in a crosswalk table, the central question is whether the unique qualities of a particular culture expressed through a controlled vocabulary—or classification—can be appropriately transferred during the mapping process.

In addition to language and cultural variants, KOS have different microstructures and macrostructures: they represent different subject domains or have different scope and coverage; they have semantic differences caused by variations in conceptual structuring; their degrees of specificity and use of terminology vary; and, the syntactic features (such as word order of terms and the use of inverted headings) are also different.

Metadata Interoperability

Metadata is also an extensively discussed topic within the domain of information exchange and integration activities. Metadata are structured, encoded data that describe characteristics of information-bearing entities (e.g., individual objects, collections, or systems) to aid in the identification, discovery, assessment, management, and preservation of the described entities. Metadata is often simply defined as "data about data" or "information about information."[9] In the literature, the words "schema" and "element set" have been used interchangeably to refer to metadata standards. In practice, metadata element sets are standards for data structures and semantics. An element set is a group of elements useful for describing resources of a particular type, or for a particular purpose. Examples are the 15-element DC Metadata Element Set (DCMES)[49] and DC Metadata Terms (an extended element set which complements the DCMES).[50] The word "schema" usually refers to an entity that includes the semantic and content components of the element set(s) as well as the encoding of the elements with a markup language such as Extensible Markup Language (XML). Examples include the XML schemas for simple and qualified DC. In this discussion, when the term "schema" is used, it refers to a metadata standard, although the major focus is often on the semantics and content of the schema rather than the encoding.

The rapid growth of Internet resources and digital collections has been accompanied by a concurrent proliferation of metadata standards, each of which was designed to be based on the requirements of particular user communities, intended users, types of materials, subject domains, project needs, and much more. Problems arise in the creation of large digital libraries or repositories when metadata records are prepared according to so many diverse standards.

In recent years numerous projects have been undertaken by the many players and stakeholders in the information community toward achieving interoperability among different metadata standards and their applications. Ideally, a uniform standard approach would ensure maximum interoperability among resource collections. If all participants of a consortium or repository were required to use the same data structure standards, such as the MARC21 format[51] or DCMES, a high level of consistency would be created and therefore maintained. This, of course, has been the approach in the library community for over a century and is the optimal solution to the interoperability problem. The uniform standardization method is only viable in the early stages of building a digital library or repository, before different schemas have been adopted by the participants. Although conceptually a simple solution, it is not always feasible. This is especially true in heterogeneous environments serving different user communities where components or collections contain different types of resources already described by particular, specialized schemas. Therefore, other mechanisms of achieving interoperability must be adopted. Implementing interoperability may be considered at different methodological levels:

1. Structure and semantics level—Efforts are focused on the structure and semantics of metadata elements, independent of any applications. Outcomes include derived element sets or encoded schemas, crosswalks, application profiles, and element registries.

2. Record level—Efforts are intended to integrate metadata records through the mapping of elements according to semantic meanings of the elements. Common results include converted records and new records resulting from combining values of existing records.
3. Repository level—With harvested records from varying sources, efforts at this level focus on mapping value strings associated with particular elements (e.g., terms associated with "subject" or "format" elements). The result enables cross-collection searching.[52]

Common Methodologies

Knowledge organization systems and metadata interoperability efforts have implemented similar methodologies. In the following analysis, we use *vocabulary* to refer to both KOS vocabulary and metadata vocabulary (metadata element set). The projects mentioned in this section are examples only (see also longer discussions).[29,41,52]

Derivation

A new vocabulary may be derived from an existing vocabulary which is seen as a "source" or "model" vocabulary. This ensures a similar basic structure and contents, while allowing different components to vary in both depth and detail for the individual vocabularies. Specific derivation methods include adaptation, modification, expansion, partial adaptation, and translation. In each case, the new vocabulary is dependent upon the source vocabulary (see Fig. 1). A current example is the Faceted Application of Subject Terminology (FAST)[53] vocabulary which derives subject terms from the LCSH and modifies the syntax to enable a post-coordinate mechanism.[54] Among the metadata standards, a significant number of lighter element sets (e.g., Text Encoding Initiative (TEI) Lite,[55] MARC Lite,[56] CDWA Lite)[57] and various formats or different encoded schemas have been derived from comprehensive ones. Derivation can also occur in the encoding format (e.g., MARCXML,[58] CDWA Lite), but the basic original content elements are retained. Many derivations can be regarded as occurring inside a family, as with the MARC family which includes MARC21, MARCXML, Metadata Object Description Schema (MODS),[59] and MARC Lite. A derived vocabulary could also become the source of a new vocabulary (as in the case of some translated vocabularies). Another variation might include the adaptation of an existing vocabulary, with slight modifications to accommodate local or specific needs. The degree of modification is relatively low in contrast to specially localized vocabularies such as application profiles (Fig. 1).

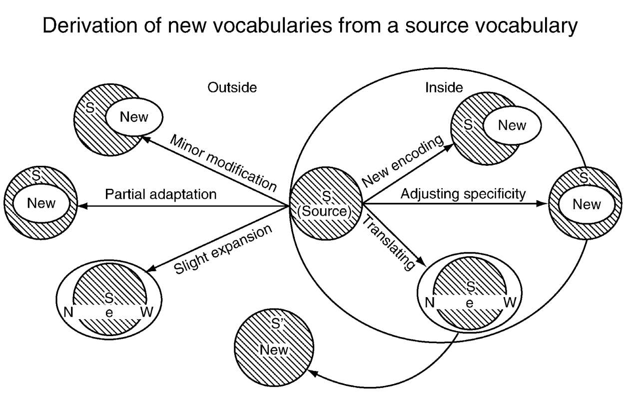

Fig. 1 Derivation of new vocabularies from a source vocabulary.

Localization and expansion

Even within a particular information community, there are different user requirements and distinctive local needs. The details provided in a particular vocabulary may not meet the needs of all user groups.

Based on the premise that metadata standards are necessarily localized and optimized for specific contents, the emergent concept of *application profiles* is typical for considering individual needs.[60] While existing element sets are used as the basis for description in a unique digital library or repository, individual needs are met through a set of specific application guidelines or policies established for interest or user groups. Application profiles generally consist of metadata elements drawn from one or more metadata element sets that are combined into a single compound structure and encoded in a schema by implementers, and then optimized for a specialized local application.[61,62] It should be noted that the DCMI community has recently developed a framework application profiles[63] based on the DCMI Abstract Model,[35] that emphasizes the *machine-processable* application profiles which encode metadata elements in machine-processable schemas employing markup languages.

An application profile may also be based on a single element set and then tailored to different user communities. For example, the DC-Library Application Profile (DC-Lib) elucidates the use of the DC metadata element sets in libraries and library-related specific applications and projects.[64] In practice, the development of an application profile often involves the following steps: 1) selecting a "base" metadata namespace; 2) selecting elements from other metadata namespaces; 3) defining local metadata elements and declaring new elements' namespaces; and 4) enforcing application of the elements (including cardinality enforcement, value space restriction, and relationship and dependency specification)[62,65] (Fig. 2).

In thesaurus and classification development, a method known as *leaf nodes* has been used in which extended schemes for subtopics are presented as the nodes of a tree structure in an upper vocabulary. When a leaf node in one thesaurus is linked to a high level (e.g., "wetlands"), and more specific subtopics of that concept exist in a specialized vocabulary or classification system (e.g., "wetlands classification scheme"), then the leaf

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node can refer to that specialized scheme.[41] As with the application profile approach, a new vocabulary can be built on the basis of more than one existing vocabulary. A major task of the developers is to not be unnecessarily redundant. Rather, their primary role is to extend from nodes and grow localized vocabulary leaves (see Fig. 3).

With careful collaboration and management, *satellite vocabularies* can be developed around a superstructure in order to meet the needs of managing specialized materials or areas. The superstructure can exist physically (e.g., LCSH) or virtually (e.g., Getty's Vocabulary Database).[66] LCSH-based thesauri include the Legislative Indexing Vocabulary (LIV),[67] the Thesaurus for Graphic Materials (TGM),[25] and the Global Legal Information Network (GLIN).[68] The English Heritage Project's National Monuments Thesauri[69] are composed of several separate online thesauri for monument types: archaeological objects, building materials, defense, evidence, maritime cargo, craft type, place name, and so on. These thesauri are displayed in an integrated space through a frame-based Web site. Terms are grouped by classes rather than by broadest terms (Top Term) and are cross-linked (Fig. 3).

Satellites under a superstructure are usually developed deliberately as an integrated unit and require top-down collaboration for management. An alternative approach, though apparently similar in terms of processes, is to plug-in different pieces to an existing *open umbrella structure*. The reason is that, in the example of ontology development, the upper level of an ontology (i.e., the more general concepts) is more fundamental for information integration. Automatic methods may be used for the semantic organization of lower-level terminology.[70] The responsibility of ensuring interoperability is that of the developers who will create the plug-ins to coordinate under the umbrella. Patel et al.[19] identify a three-tier structure of upper-core-domain ontologies: 1) *upper ontologies* define basic, domain-independent concepts as well as relationships among them (e.g., CYC Ontology[71] and WordNet);[72] 2) *core* (*or intermediate*) *ontologies* are essentially the upper ontologies for broad application domains (e.g., the audiovisual domain); and 3) *domain ontologies* in which concepts and relationships used in specific application domains are defined (e.g., a "goal" in the soccer video domain). The core ontologies comprise concepts and relationships that are classified as basic in the broad application domain context, e.g., an event in the audiovisual domain. The concepts defined in domain ontologies correspond to the concepts and relationships established in both upper and core ontologies, which may be extended with the addition of domain knowledge (Fig. 4).

The *Digital Curation Center's Digital Curation Manual*: *Installment on "Ontologies"*[70] recommends that the editors of KOS first agree on a common upper-level ontology across disciplines in order to guarantee interoperability at the fundamental and functional levels. On the other hand, it is important to fully grasp the conditions and cost-benefit ratio of connecting an upper ontology and domain KOS: 1) the intended purpose—indexing and retrieval vs. automatic inferencing; 2) the alignment of the ontology and domain KOS; 3) the number of different KOS intended to be modeled; and 4) the use cases to be supported.[73]

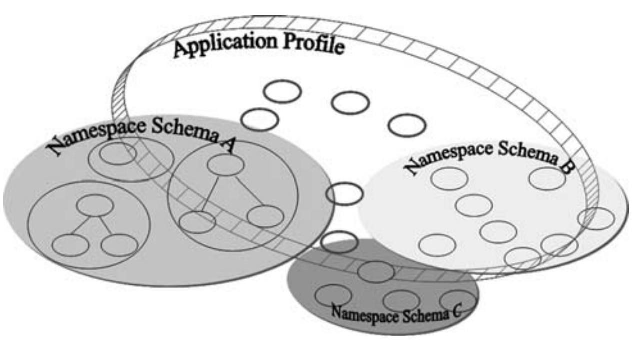

Fig. 2 An application profile consisting of elements drawn from one or more metadata element sets.

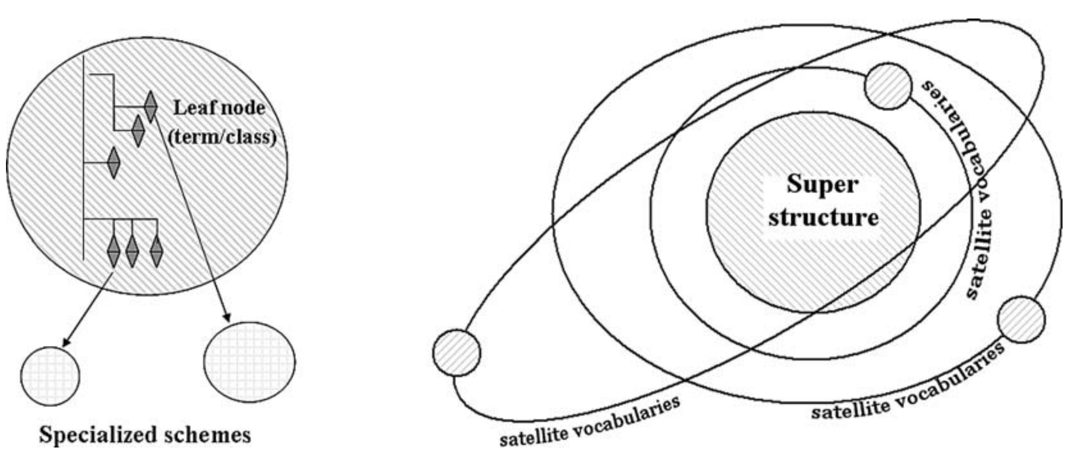

Fig. 3 Leaf node linking and satellites.

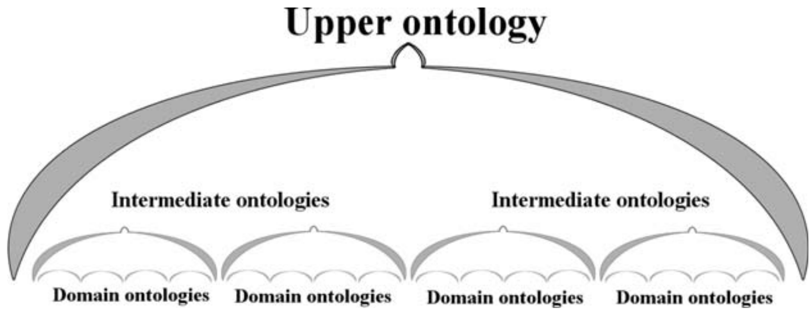

Fig. 4 Intermediate and domain vocabularies plugged-in under an open umbrella structure.

Mapping, crosswalking, and data conversion

The process of mapping essentially consists of establishing equivalencies between terms in different controlled vocabularies and between metadata element sets. In both cases the vocabulary may be presented in verbal terms and/or notation numbers in a scheme. Depending on the number of schemes involved in the process, two different models may be considered.

In *direct mapping*, one-to-one mapping is usually applied when two (or a limited few) schemes are involved. Almost all metadata standards have mapped their elements to the DC 15 elements defined by ISO 15836-2003.[74] The MACS project mapped subject headings in three monolingual lists: Schlagwortnormdatei/Regeln für den Schlagwortkatalog (SWD/RSWK), Répertoire d'autorité-matière encyclopédique et alphabétique unifié (Rameau), and LCSH.[46] Nevertheless, when using the direct mapping model, four schemes would require twelve (or six pairs of) mapping processes. This not only is extremely tedious and labor intensive, but also requires enormous intellectual exertion.

Cross-switching is another kind of model usually applied to reconcile multiple schemes. In this model, one of the schemes is used as the switching mechanism between the multiple schemes. Instead of mapping between every pair in the group, each scheme is mapped to the switching scheme only. Such a switching system can be a new system (e.g., the UMLS' Metathesaurus)[75] or an existing system (e.g., the Dewey Decimal Classification (DDC)). Another example is Getty's crosswalk which allows multiple metadata schemas to all crosswalk to CDWA.[76] For KOS and subject directories, this is the approach adopted by Renardus and a number of other projects. The Renardus project maps local class schemes to a common scheme: the DDC. Each DDC class that Renardus presents links to "related collections" which enables the user to then jump to the mapped classes in the participating local gateways while continuing to browse in the local classification structure. In addition, a virtual browsing feature allows the merging of all local related records from all mapped classes into one common Renardus result set[77] (Fig. 5).

In the metadata community, the word *crosswalk* is established and commonly used among practitioners. Previously this format was also referred to as a *concordance* when subject headings were mapped and stored. A metadata crosswalk is "a mapping of the elements, semantics, and syntax from one metadata scheme to those of another."[9] The mechanism used in crosswalks is usually a chart or table that represents the semantic mapping of data elements in one data standard (source) to those in another standard (target) based on similarity of function or meaning of the elements.[78] According to the NISO document, *Issues in Crosswalking Content Metadata Standards*, common properties may include a semantic definition of each metadata element and other issues including:

- Whether a metadata element is mandatory or optional based on certain conditions.
- Whether a metadata element may occur once or multiple times within the same record.
- Constraints as to the organization of metadata elements relative to each other, (e.g., hierarchical parent–child relationships).
- Constraints imposed on the value of an element (e.g., free text, numeric range, date, or a controlled vocabulary).
- Optional support for locally defined metadata elements.[79]

Major efforts in metadata mapping have produced a substantial number of crosswalks. Almost all schemas have created crosswalks to widely applied schemas such as DC, MARC, or Learning Object Metadata (LOM).[80] Metadata specifications may also include crosswalks to a previous version of a schema as well as to other metadata schemas, e.g., the VRA Core 3.0[81] and 4.0.[36]

Two approaches have emerged in crosswalking practice. The *absolute crosswalking* approach requires exact mapping between involved elements (e.g., vra.title → dc.title) of a source schema (e.g., VRA Core) and a target schema (e.g., DC). Where there is no exact equivalence, there is no crosswalking (e.g., vra.technique → [empty space]). Absolute crosswalking ensures the equivalency (or closely equivalent matches) of elements,

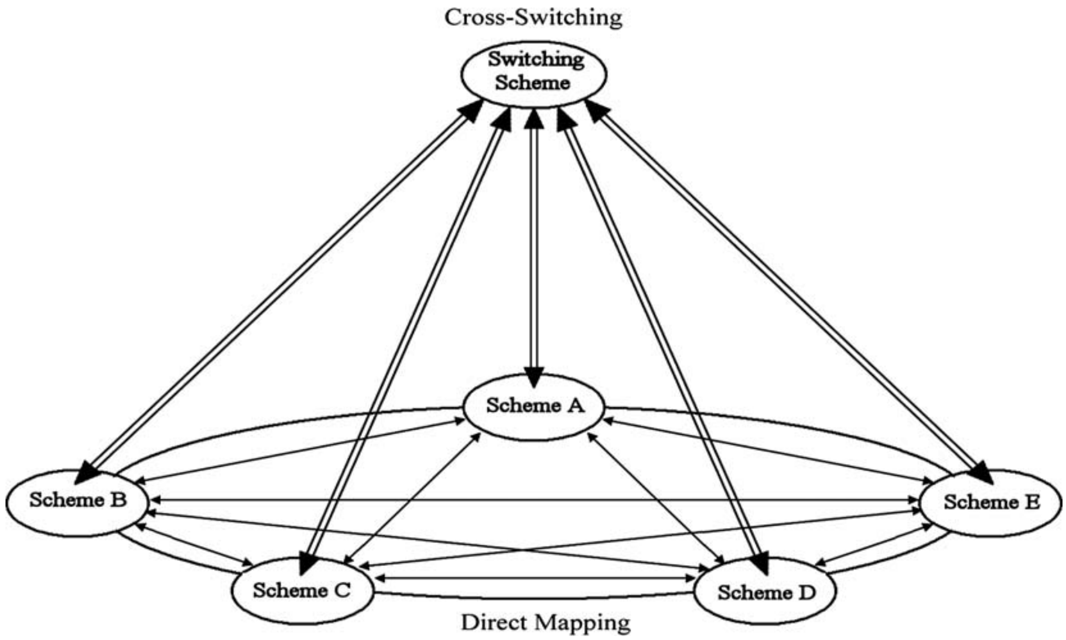

Fig. 5 Direct mapping and cross-switching.

but does not work well for data conversion. The problem is the data values that cannot possibly be mapped, particularly when a source schema has a richer structure than that of the target schema. To overcome this problem, an alternative approach, *relative crosswalking*, is used to map all elements in a source schema to at least one element of a target schema, regardless of whether the two elements are semantically equivalent or not (e.g., vra.technique → dc.format). The relative crosswalking approach appears to work better when mapping from a complex to a simple (or basic) schema (e.g., MARC to DC), than the reverse.

Functionally, crosswalks should allow systems to effectively convert data and enable heterogeneous collections to be searched simultaneously with a single query as if within a single database. The reality is that crosswalks constructed from real data conversion may be very different from those based on metadata specifications. The major challenge in *converting records* prepared according to a particular metadata schema into records based on another schema is how to minimize loss, or distortion, of data. In studies by Zeng and colleagues,[82,83] it was found that when data values were involved, converting may become imprecise and conversion tasks become more complicated. When the target schema is more inclusive and has defined elements and sub-elements with greater detail than the source schema, the values in a source metadata record may need to be broken down into smaller units (e.g., from DC elements to MARC records subfields). As mentioned above, the risk is that data values may be lost when converting from a complex to a simple structure in absolute crosswalking. Equally, granularity may be lost when converting from a complex to a simple structure in relative crosswalking. Other vexing problems include converting value strings associated with certain elements that have rules for required, mandatory, or optional usage (in addition to the decisions about which controlled vocabularies are selected). Detailed explanations should be provided for as many contingencies that can be foreseen. Regrettably, most crosswalks focus only on element mappings that are based on *metadata specifications*, and not on *real data conversion results*. A recent study on metadata quality provides strong evidence for the impact of crosswalks on quality when converting large amounts of data.[83] The most serious difficulties include misrepresented data values, important data values lost, incorrectly mapped elements and data values, and, missing elements. It is understood that collaborative approaches are needed in order to solve these problems. Zeng and Shreve recommend a set of approaches to correct many of the errors found in a metadata repository regarding data conversion:

1. Recreating and improving crosswalks.
2. Reharvesting records if quality reviews indicate the need.
3. Sponsoring and enforcing comprehensive standards and best practice guidelines for all elements.
4. Enriching data—both pre- and post-harvest—by automatic processes.
5. Supplying consistent mapping tables to past, present, and future data providers when harvesting is to be conducted.
6. Encouraging and ensuring active collaboration and open communication between repositories and local collection groups.

Co-occurrence mapping is similar to what was done in the MACS project where values in the subject fields of a record from different vocabularies are treated as equivalents. When a metadata record includes terms from multiple controlled vocabularies, co-occurrence of subject terms allows for an automatic, loose mapping between vocabularies. As a group, these loosely mapped terms can answer a particular search query or a group of questions. Existing metadata standards and best practice guides have provided the opportunity to maximize the co-occurrence mapping method. A good example is the VRA Core Categories versions 3.0 and 4.0, which recommend the use of AAT, LCSH, Thesaurus of Graphic Materials (TGM), ICONCLASS,[84] and the Sears List of Subject Headings[85] for culture and subject elements. Also, a Feature Class field of the gazetteer of the Alexandria Digital Library[86] includes terms from two controlled vocabularies (ADL Feature Thesaurus and GNS Feature Classes) in one record.[87] Additionally, metadata records often include both controlled terms and uncontrolled keywords. Mapped subject terms can be used as access points that lead to full metadata records. These *fielded-in* value strings associated with multiple sources may be integrated to enrich metadata records through automatic processes. As more co-occurrence types of mapping are widely applied, loosely mapped values will become very useful in productive searching with highly relevant results.

Crosswalking services mark a further stage of crosswalk development toward meeting the challenge of ensuring consistency in large databases that are built on records from multiple sources. Efforts to establish a crosswalking service at OCLC have indicated the need for robust systems that can handle validation, enhancement, multiple character encodings, and allow human guidance of the translation process.[88] The OCLC researchers developed a model that associates three pieces of information: 1) crosswalk; 2) source metadata standard; and 3) target metadata standard. Researchers at the National Science Digital Library (NSDL)[89] have also included a crosswalking service in their sequence of metadata enhancement services. These crosswalking services are a type of metadata augmentation operation that generates new fielded metadata values that are based on crosswalking from a source (schema or vocabulary) to a target (schema or vocabulary). The operation can be performed on either controlled or uncontrolled vocabulary value strings associated with specific elements.[90] Both element-based and value-based crosswalking services assist in achieving semantic interoperability and improve the reusability of metadata in a variety of knowledge domains.

Registries, repositories, and web services

Registries and repositories for metadata and KOS vocabularies, powered by semantic technologies such as RDF, SKOS, and OWL, have emerged in recent years. Their primary functions include registering, publishing, managing diverse vocabularies and schemas, as well as ensuring they are crosslinked, crosswalked, and searchable. Their presence promotes the wider adoption, standardization, and overall interoperability of metadata by facilitating its discovery, reuse, harmonization, and synergy across diverse disciplines and communities of practice.[91]

The purpose of *metadata registries* is fairly straightforward: to collect data related to metadata schemas. Since the reuse of existing metadata terms is essential to achieving interoperability among metadata element sets, the identification of existing terms becomes a precondition of any new metadata schema development process. Metadata registries are expected to provide the means to identify and refer to established schemas and application profiles, as well as the means to crosswalk and map among different schemas.[62] The importance of the management and disclosure roles of registries will increase as more metadata and application profile schemas are developed.

The basic components of a metadata registry include identification of data models, elements, element sets, encoding schemes, application profiles, element usage information, and element crosswalks. In addition to these common components, each registry usually has a specific scope and range. Registries can be categorized as:

- Cross-domain and cross-schema registries, e.g., UKOLN's SCHEMAS Registry.[92]
- Domain-specific, cross-schema registries, e.g., UKOLN's MEG (Metadata for Education Group) Registry.[93]
- Project-specific registries, e.g., The European Library (TEL) metadata registry[94] whose purpose is recording all metadata activities associated with TEL.
- Standard-specific registries, e.g., DCMI Metadata Registry.[91]

Metadata standards often specify vocabulary encoding schemes (such as controlled term lists, subject heading lists, name authority files, and thesauri) for use in value spaces associated with certain metadata elements or fields. Consequently, metadata registries may also contain, or link to, terms and codes from these schemes (e.g., DCMI Registry also includes the DCMI Type Vocabulary). Thus the term "metadata registry" could also refer to an integrated structure housing both metadata and terminologies.

At a minimal level, *terminology registries* hold *scheme information*, and list, describe, identify, and point to sets of KOS and other types of vocabularies (e.g., dictionaries) available for use in information systems and services. At a higher level, a terminology registry can comprise the *member* terms, classes, concepts, and relationships contained in a vocabulary (either monolingual or multilingual). Related to the terminology registries are *services*, which may also be listed in a terminology registry or separately hosted in a *service registry*. These services, based on terminology, are used for automatic classification, term expansion, disambiguation, translation, and semantic reasoning.[95] When registering member terms and classes, the scale of the vocabularies becomes significant, often containing hundreds and thousands of entries, along with the complicated relationships among them.

Efforts to register KOS begin with the set of common attributes that describe them. In 1998, researchers belonging to an informal interest group Networked Knowledge Organization Systems/Services (NKOS)[96] began developing a set of elements for a registry for thesauri and other subject vocabularies. A taxonomy of KOS was developed so as to better differentiate the types and functions of subject vocabularies.[97] In 2001, the registry reference document was extended to cover more types of KOS in the second version renamed the NKOS Registry.[98] It includes two blocks of elements. The first block of elements, *KOS Title* through *Rights*, closely corresponds to the Dublin Core Element Set and is intended for creating metadata descriptions that will facilitate the discovery of KOS resources. The second block of elements is intended for the recording of specific characteristics of a KOS resource which will facilitate evaluation of the resource for a particular application or use. Another work, Vocabulary Markup Language: Metacode strawman DTD, was also proposed in 2001[99] and has been an area of ongoing research by NKOS members.

The National Science Digital Library (NSDL) Registry project, funded by the National Science Foundation in 2005, was commissioned to develop and deploy an NSDL Registry to complement the existing NSDL Central Metadata Repository. The Registry is designed to conform to the DCMI Registry application, and so enables multiple diverse collection providers as well as other NSDL projects to identify, declare, and publish their metadata schemas (element/property sets) and encoding schemes (controlled vocabularies). Further, the project intends to provide support for registration of vocabulary encoding schemes and metadata schemas for use by human and machine agents, as well as to support machine mapping of relationships among terms and concepts in those schemes (semantic mappings) and schemas (crosswalks). It is one of the production deployments of SKOS.[100] The functions of the registry serve across metadata, terminology, and services.

Over the past several years, an eXtended MetaData Registry project has been jointly sponsored by several major government agencies[101] and is currently hosted by the Lawrence Berkeley National Laboratory at the University of California. This project was initiated with the intent of developing improved standards and technology for storing and retrieving semantics of data elements, terminologies, and concept structures in registries. It plans to propose extensions of the ISO/IEC 11179 Metadata Registry (MDR)[102] standards, create a prototype extended metadata registry, and load selected KOS into the prototype. The diverse types of complex semantic metadata (i.e., concepts), are registered in more formal, systematic ways (e.g., description logic) to facilitate machine processing of semantics in order to: 1) link together data elements and terms across multiple systems; 2) discover relationships among data elements, terms, and concepts; 3) create and manage names, definitions, terms, etc.; and 4) support software inference, aggregation, and agent services.[103] This last function leads to what we will discuss next: *terminology services* (Fig. 6).

Terminology services are usually related to or include a registry, but are not limited to registering vocabularies. A terminology service can be defined as a group of *services* that present and apply vocabularies, member concepts, terms, classes, relationships, and detailed explanations of terms which facilitate semantic interoperability. The goals are ambitious: to enable searching, browsing, discovery, translation, mapping, semantic reasoning, automatic classification and indexing, harvesting, and alerting. Terminology services can be machine-to-machine or interactive; user-interfacing services can also be applied at all stages of the search process. For example, in supporting the needs of searching for concepts and the terms representing the concepts, the services can assist in resolving search terms, disambiguation, browsing access, and mapping between vocabularies. As a search support for queries, the services facilitate query expansion, query reformulation, and combined browsing and search. These can be applied as

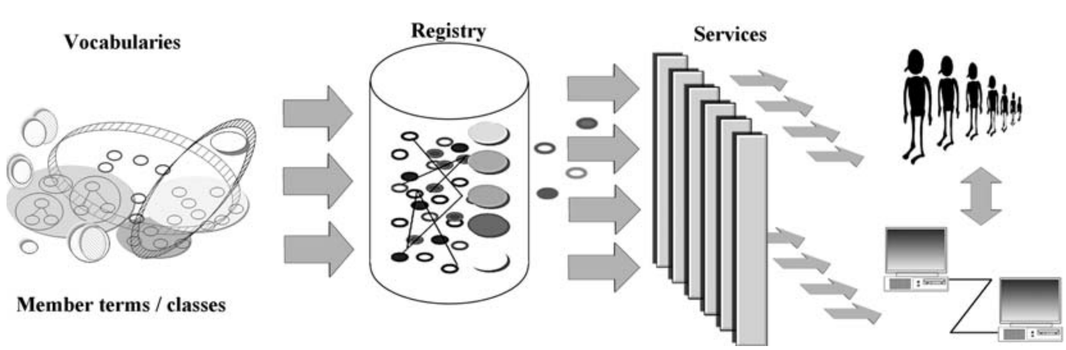

Fig. 6 Terms from metadata and KOS vocabularies registered and used/reused through Web services.

immediate elements of the end user interface, or they can act in underpinning services behind the scenes, depending upon the context.[104] Technologically, they use Web services to interact with controlled vocabularies, and this represents an entirely new dimension in KOS research and development.

A relevant example is OCLC's Terminology Services project.[105] As of June 2008, mappings had been made for eight knowledge organization resources through direct mapping (associations between equivalent terms) and co-occurrence mapping (associations based on the co-occurrence of terms from different schemes in the same metadata or catalog record). Co-occurrence mappings are considered to be mapped more loosely than direct mappings, and usually have an intellectual review component.[106] These services have made records accessible to users through a browser and to machines via the OAI-PMH Web services mechanisms.[107] OCLC immediately began in 2007 to offer its Terminologies Service™ (more than 10 controlled vocabularies served through a single interface thus far) to its thousands of member institutions throughout the world. In addition to the ability of searching descriptions of controlled vocabularies and their member terms/headings, finding single terms/headings by their identifiers, and viewing term relationships, users can retrieve terms/headings in multiple representations such as HTML, MARC XML, SKOS, and Zthes specifications for thesaurus representation, access, and navigation.[108]

The High Level Thesaurus (HILT) projects[109]—a series of research projects funded by the U.K. Joint Information Systems Committee (JISC)—demonstrate a different approach. HILT is concerned with facilitating subject-based access across the broad spectrum of JISC collections that is combined with the automated discovery of relevant collections. HILT has investigated pilot terminology services in collaboration with OCLC Research and Wordmap. DDC was chosen as the central spine for mapping among major vocabularies such as DDC, LCSH, UNESCO Thesaurus,[110] Medical Subject Headings (MeSH),[111] and AAT. HILT Phase 3 focuses on developing a machine-to-machine demonstrator based on Web services, the Search/Retrieve Web Service (SRW) protocol,[112] SKOS Core, and SKOS-type concept URIs. It is being designed so that end users will not access HILT directly; rather, they will be routed through Web-based user services.[19,113]

Other current operational and experimental terminology services have been reviewed in detail in a report entitled *Terminology Services and Technology* prepared for JISC by Tudhope, Koch, and Heery in 2006.[104] Since then, more projects have been initiated. The Semantic Technologies for Archaeological Resources (STAR) project, funded by the British Arts & Humanities Research Council (AHRC), is based at the University of Glamorgan. It aims to develop new methods for linking digital archive databases, vocabularies (and associated gray literature), and to exploit the potential of a high-level, core ontology, and natural language processing techniques.[114] In collaboration with English Heritage,[115] a set of extensions to the CIDOC CRM[21] core ontology have been produced as RDF files. Thesaurus data received from the English Heritage National Monuments Record Centre was converted into the standard SKOS RDF format for use in the project.[116] The project has developed an initial set of Web services that are based on SKOS representations. The designed function calls can be integrated into a textual- or metadata-based search system. In addition to search and browse concepts in a thesaurus, the service supports semantic expansion of concepts for purposes of query expansion. By an automatic traversal of SKOS relationships, it yields a ranked list of semantically close concepts.[73]

Another new UKOLN project, Terminology Registries and Services (TRSS), is examining how a registry might support the development of terminology and other services within the context of a service-oriented environment. In particular, it is analyzing issues related to the potential delivery of a Terminology Registry as a shared infrastructure service within the JISC Information Environment.[95]

Although there is no official recognition or definition regarding the relationships between KOS and ontologies (particularly formal ontologies), there are *ontology repositories* that host formal ontologies, thesauri, and taxonomies together. Practically speaking, artifacts on the ontology spectrum are considered to have not only the OWL ontologies and axiomatized logical theories, but also include traditional and new structures/schemes, from controlled vocabularies, taxonomies, and thesauri to folksonomies, and from KOS schemes to data schema and data models.[117]

An ontology repository is a facility where ontologies and related information artifacts can be stored, retrieved, and managed. One example is BioPortal,[118] an open-source repository of ontologies, terminologies, and thesauri that is relevant to biomedicine, developed by the U.S. National Center for Biomedical Ontology. As of June 2008, users may access the BioPortal content (over 100 ontologies) interactively via Web browsers or programmatically via Web services. Downloading, searching, and visualizing are three basic functions of these OWL or Protégé ontologies. Users can search for content within a specific ontology, a group of ontologies, or across all ontologies in the library by: Class/Type Name, Class ID, and other attributes such as definitions and synonyms.

An Open Ontology Repository (OOR)[119] initiative planning meeting was conducted in January 2008 by ONTOLOG,[120] an open, international, virtual community of practice. OOR discussions have progressed through a series of mini-conferences that have culminated in the Ontology Summit. With the word "open" added, the ontology repository aims at implementation via open access and compliance with open standards: open technology (with open source), open knowledge (open content), open collaboration (with transparent community process), and open integration with "non-open" repositories through an open interface.[121] The project mission and charter of OOR are to

1. establish a hosted registry-repository.
2. enable and facilitate open, federated, collaborative ontology repositories.
3. establish best practices for expressing interoperable ontology and taxonomy work in registry-repositories.[119,122]

Some current ontology registries/repositories do not provide concept-based mapping. Consequently, most results are based on terms representing concepts, for example, a search for "aging" in an ontology repository may find classes such as "biological im*aging* methods," "im*aging* device," and so forth that are not relevant to the query. The development of concept-based mapping will be a major and much-needed service, and it will also bring in its wake new challenges for ontology repositories.

CONCLUSION

Semantic interoperability plays a central role in information communication; it has a direct impact on a whole range of interoperability issues. This entry has discussed the importance of semantic interoperability in the networked environment, introduced various approaches contributing to semantic interoperability, and summarized different methodologies used in current projects that are focused on achieving semantic interoperability. The proliferation of repositories, interfaces, metadata models, and semantic technologies accentuates the need for semantic interoperability. The open, networked environment encompasses multiple user communities that employ a plethora of standards for describing and providing access to digital resources. To enable federated searches and to facilitate metadata sharing and management, many efforts have been initiated to address interoperability issues, to overcome numerous obstacles, and to address problems encountered along the way. Nevertheless, new and unforeseen interoperability difficulties continue to emerge. The complexity of interoperability does not stop at the international or industry standards level. Guidelines, rules, measurements, and certification are indispensable at the implementation level to ensure that available standards and technologies are optimized. The foundation of all of these requirements is global collaboration. It should be obvious that in order to build the true Semantic Web, not only must existing issues be addressed, but semantic problems of the future also need to be anticipated where possible.

Interoperability requires commonly agreed-upon standards and protocols at different levels for different levels of interoperability. The prospect is emerging for a broad set of standards across different aspects of terminology services: persistent identifiers, representation of vocabularies, protocols for programmatic access, and vocabulary-level metadata in repositories.[19] XML, RDF, RDFS, OWL, and SKOS are the high-level standards that will enable the achievement of semantic interoperability in the networked environment.

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