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NISTIR 6301

An Analysis of Existing Ontological Systems for Applications in Manufacturing and Healthcare

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NO. 6301
1999

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March 1999



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1.0 Introduction

The objective of this work described in this paper is to move closer to the ultimate goal of seamless system integration using the principle behind ontological engineering to unambiguously define domain-specific concepts. A major challenge facing industry today is the lack of interoperability between heterogeneous systems. This challenge is apparent in many sectors, including both healthcare and manufacturing. Current integration efforts are usually based solely on how information is represented (the syntax or terminology) without a description of what the information means (the semantics). With the growing complexity of information and the increasing need to completely and correctly exchange information among different systems, the need for precise and unambiguous capture of the meaning of concepts within a given system is becoming apparent.

The approach for this project is to analyze current ontological systems to determine which is most suitable to model the concepts in both the healthcare and manufacturing domains. Examples of ontological systems include the Unified Medical Language System (UMLS¹), CYC^{2,3}, and the Ontolingua server. For the manufacturing-related ontologies, the project will move to formally identifying and modeling concepts (and definitions of those concepts) from various manufacturing domains and projects (e.g., process specification, product modeling, resource representations, etc.) in this ontological system. At this point, an analysis can help to identify inconsistencies in the use of terms among various domains as well as help to establish a means to generalize these terms to a level that is common among the domains in question.

The output of the work documented in this paper will be a taxonomy of terms and concepts along with formal definitions of exactly what each of those terms/concepts mean and how they interrelate. Although it would be impossible to create a complete taxonomy of every interpretation of every term, a high-level, extensible subset of this taxonomy will be created to serve as a basis for future, domain-specific additions and specializations. This shared understanding of concepts could then be used to integrate applications and systems that function towards a common goal.

This paper documents the results of the first phase of this project – that of analyzing existing ontological systems to determine which is most appropriate for the manufacturing and healthcare domains. In particular, this phase involved the exploration of efforts that are studying both the uses of ontologies in the general sense and those that are using ontologies for domain specific purposes.

2.0 Why Ontologies for Manufacturing?

This section considers what value the investigated ontologies might provide to the area of information technology within manufacturing. Communication and context are important notions to understanding the role of the investigated ontologies vis a vis other technologies. This and the related concepts of formality, ground, and context availability are discussed. Three areas of potential benefit are then considered: unambiguous communication, standards making/semantic alignment efforts and the future industrial information infrastructure.

¹ The Unified Medical Language System (UMLS) is a registered trademark of the U.S. National Library of Medicine.

² CYC is a registered trademark of Cycorp Inc.

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2.1 COMMUNICATION, MEANING AND CONTEXT

In this paper 'communication' has the following meaning: One communicates to another with the expectation that at some time thereafter the receiver will produce a behavior that is in some way consistent with the initiator's intention. For communication to succeed, the initiator must have (or the system design must reflect) some understanding of the context under which the receiver is operating and the relationship between the message it designs and the behavior it desires from the receiver.

This definition of communication begs the question of what is 'meaning'. Along the lines of Bloomfield [BLO33] there is at the very least this sense of meaning to communication: it sets conditions for satisfaction. If I say "Pick up the book." and you do so, this is evidence of a relationship between a representation and a perceived reality. Philosophers might argue that there is more or less meaning in 'meaning', but computer scientists need not care; they are interested in the behavior of programs.

The phrase 'understanding of the context' in the above definition of communication is fraught with implication. Roughly, context is an environment, a 'place' where things occur or an utterance is made. The anticipation of, and preparation for, a particular environment is a basic design question.

It is largely a matter of how context is established and used that differentiates various software technologies. A complete study of this issue is well beyond the scope of this paper, but for the purpose of understanding the value of the investigated ontologies it is worthwhile to establish some dimensions on the term 'context' and place the investigated ontologies and related technologies in this framework.

In order to cut the notion of context down to a manageable size, we first make the distinction of three fundamentally different means by which software technology embodies context. Along the lines of Varala et al. [VAR91], these technologies are 'enactive', 'emergent', and 'symbolic'.

Neural nets are representative of enactive technology. In neural nets an associative memory embodies the relationship between environmental demands and behaviors in response to those demands, that is, context is reflected in the trained associative memory. Enactive technology is outside the scope of this paper.

Genetic algorithms are representative of emergent technology. In the emergent approach context is reflected in the statistical distribution of individual designs within a spectrum of possible designs. Each individual is an attempt to encode (and cope with) the context. Emergent technology is outside the scope of this paper.

Symbolic technology includes procedural (e.g. object-oriented) constraint and logic programming, ontologies and natural language. Unlike the others, symbolic technology is inextricably linked with language and hence meaning and context can be communicated among individuals, not just embodied by them. Roughly speaking, dictionaries, thesauri and computer-based ontology systems are each built upon networks of symbols related to each other by various notions of resemblance. In terms of such networks we can state two fundamental problems of communication as (1) that individuals seldom share a common network of symbols and (2) that designating a place in a network (establishing a context) is difficult.

Regarding the first of these problems, it is clear that people do not communicate using identical networks. Our use of language is idiosyncratic and a result of life experience. In some sense the problem is worse for computers than it is for people. As Quine points out, among people "The coherence is no coincidence, for the network is self-corrective." Were I to use the word "hello" to mean "goodbye", someone would correct me and I would discontinue this erroneous practice. Such correction capabilities usually don't accompany software.

With respect to the second problem, most people can recall entering into the middle of a conversation and totally misinterpreting what was being discussed. In software communications, context is almost always assumed, with potentially disastrous consequences.

In computer technology, at least, it is somewhat artificial to say that these are two different problems. Although errant software may not have critics to re-align the network, the software development process does. In essence, all problems of context in software (excepting perhaps some artificial intelligence applications) are resolved by the software developers on both side of an information exchange coming to agreement on what the information exchanged means (problem 1). The arrangement they choose might be ad hoc or by reference to a consensus standard, for example.

The software developers above might never know nor care whether they are developing interfaces based on identical understanding. What is essential is that the software behaves as expected. Much the same can be said of the interactions of people.

This discussion leads us to a few questions relevant to the positioning of the investigated ontologies vis a vis other technologies:

1. Need we do more than get the behavior right?
2. How do we know that we are in agreement well enough to get the behavior right?
3. What holds the ontology?

Of course, good answers to these questions do not come easy. We can not respond completely at this point in the investigation. Towards an answer to any of these, we consider the notions of ground, formality, seamlessness and context availability.

2.1.1 GROUND

Webster's defines 'ground' as "the foundation for an argument, belief or action". Ontologies are one technology where the notion of ground is prominent. In some sense, unambiguous communication of information is enabled by relating consensus domain terminology to widely held ground terms. There are however, overriding issues in making this goal a reality. This is discussed in the section on unambiguous communication.

Some ontology systems (for example CYC) provide a mechanism to allow reasoning under multiple sets of ground terms ('assumptions'). [deK86] Intuitively this appears useful in manufacturing situations but more consideration is necessary.

It is a mistake to assume that only ontological systems make explicit use of ground. For example, the Eiffel programming language use 'contracts', relations among communicating components whose interaction is based on precisely defined specifications of mutual obligation to support ground for action. In [JEZ98] Jézéquel and Meyer argue that an object-oriented 'reuse error' caused the \$500M crash of an Ariane rocket. They suggest that the crash could have been prevented had the notion of contracts between objects been used.

The contract paradigm, an 'operationally active' flavor of the notion of ground, enables reliable reuse in object-oriented programming. The contract paradigm complements the current thrust in standards for distributed object-oriented systems such as those of the Object Management Group [OMG98].

2.1.2 CONTEXT AVAILABILITY IN INFORMATION EXCHANGE

In the design of communicating systems one may choose to resolve all questions of the context of information exchanged at design time. Alternatively, the exchange might include context-setting information, or 'meta-level' information.

Many high-performance systems do not communicate much context information between each other; the context of the information exchanged was agreed upon by the system designers a priori and is implicit in the software. The exchange of a single property in STEP technology, on the other hand, includes several context-setting references: references to the measurement units used (e.g. newton/meters) the various representations of the property (e.g. as thermal energy, as mechanical energy) the technical discipline it concerns (e.g. 'structural analysis') and the product lifecycle (e.g. 'design'). [DAN97].

Within the investigated ontologies the meta-level is available as references that could lead all the way to ground terms. What is not as clear at this point of our investigation is in what manner meta-level information is made available in information exchange. We may study the Knowledge Interchange Format (KIF) in our second year effort as a means towards this end.

2.1.3 SEAMLESSNESS

A context or meta-level may be available but only in a different technology or facility than the problem solving machinery. This is a common occurrence (e.g. the OMG implementation repository). Seamlessness refers to the continuity (or 'transparency') of the information content with its context-setting information. That is, in a seamless environment the problem solving machinery can get context setting information without appealing to another for service.

The principle question here with respect to the investigated ontologies is how to marry the technology to the 'problem solvers'. That is, how should ontologies be interfaced to applications such as schedulers and workflow systems? We did not attempt to answer this question in this year's investigation.

2.1.4 FORMALITY

At times, formality in ontologies seems to mean the degree to which the ontology resembles mathematical logic. Resemblance to mathematical logic in itself however does not suggest a purpose for formality. We suggest the following:

- Formality is about making valid inferences (and thus getting expected behaviors)
- Formality is about traceability to ground.
- Formality is about enabling computational tools (to manage complexity etc.).

One benefit of the formal language underlying the investigated ontologies is that because it provides a computational form to the information, it supports a 'short-hand' means to generate unthought-of but (hopefully desirable) behaviors. One question facing anyone adopting such technology is whether this characteristic is in fact desirable; often it is not.

There are many notions exchanged among engineering and manufacturing systems for which it might be quite inefficient to attempt to represent the ideas in anything but traditional mathematical terms. CAD geometry is of this sort.

2.2 ANSWERS TO 'WHY ONTOLOGIES?'

The previous section provides a foundation of ideas concerning communicating systems. In this investigation we have not yet resolved many design questions regarding how this technology may be employed. Assuming that there are reasonable answers to these questions, however, we may still ask what added value the investigated ontologies might provide to the development of a manufacturing information infrastructure. Here we consider the contribution ontologies might make to eliminate ambiguity in communication, and in the standards making process.

2.2.1 UNAMBIGUOUS COMMUNICATION

We consider two questions with respect to the investigated ontologies and the goal of unambiguous communication:

1. Where does the problem of ambiguity reside?
2. Do communicating systems need access to ground terms?

In regards to the first question we note that generally speaking, manufacturing systems have lagged financial systems in their ability to exchange data. One explanation for this might be that less time and

effort has been invested in the integration of manufacturing systems. There are other equally valid explanations:

- Manufacturing data and its interrelationships are complex, perhaps much more so than financial data.
- There is no universally accepted meaning to terms used in manufacturing.

It is important to note that these two points are statements about the nature of manufacturing information itself: their solution requires knowledge of manufacturing foremost. Information technology isn't the issue here. The problem is getting individuals in whole industries to agree on the meaning of perhaps thousands of terms such as "part version" and "part revision". This is about razing the Tower of Babel and putting in its place a consistent terminology. It requires a large effort, but is also one that is (and has been) essential to the goal of unambiguous communication. Standards efforts such as IEC 61360-4, a dictionary of standard terminology for electronic components [ISO97] are representative of the sort of work that must be done.

In summary to the first (and most crucial) question we recognize that our answer leads back to the standards making process, and in effect, the choice of the investigated ontologies versus more conventional information modeling technology for the purpose of information exchange appears inconsequential over the short term (15 years?). The development of domain consensus terminology is most important presently.

With regards to the second question, (whether communicating systems need access to ground term) we consider an alternative strategy, that of the STEP standards.

In the STEP method, manufacturing notions are related to more fundamental notions through an interpretation process. The STEP interpretation process has similarities with Schank's conceptual dependencies [SCH81]. In the STEP method a collection of attributed entities (integrated resources) possessing a partially defined semantics (i.e. under-defined building block enabling wide applicability) are made to represent specific notions through their aggregation, interrelation, specification of values and subtyping. Entities in a network identify the property's context (e.g. engineering and industrial discipline) and measurement units. In STEP it is in fact this circumscribed collection of interrelated entities that represents the property, not an individual entity that possesses reference down to ground terms.

The distinction with respect to 'grounded' ontologies here is that within the STEP standards, meaning is fully described provided that a property identifies its context, measurement units and property name *and* this property name designates, without ambiguity, a notion that is the product of industry consensus on the terminology of that property.

In practice the STEP process does not always guarantee this consensus of property terminology. It is necessary for success with STEP technology, nonetheless.

The difference, then, between STEP and the investigated ontologies is the point at which each goes outside itself to establish meaning. STEP is 'flat' beginning and terminating in specific industrial domain terminology. The investigated ontologies are 'bottom-up' beginning with some fundamental notions and building towards more specific notions, which to date, have not encompassed many notions of importance to industry.

Communicating systems rarely need access to ground terms. The exception to this is those few systems that mediate data. The problem of bringing meaning to the exchanged data always leads back to reference to shared understanding. For this reason we conclude that ontologies do not offer significant benefit towards making current information exchange methods more reliable.

2.2.2 STANDARDS MAKING AND SEMANTIC ALIGNMENT EFFORTS

As suggested above, there is a need for comprehensible industrial terminology developed through consensus. As increasing amounts of the work involved with bringing a product to market are possible on the Internet and as increasing amounts of the supply chain become integrated, the audience for this

terminology widens. A terminology shared among manufacturers of centrifugal pumps is most useful when it can also be understood by makers of bearings for these pumps and builders of process plants using the pumps.

Of course, various usages of the same term have grown up in various industries (e.g. "Stator" means one thing to a manufacturer of turbine engines and another to a manufacturer of automobile alternators). Because the investigated ontologies may be founded on notions common to both usages, it is possible to recognize when usages differ.

Although this aspect of the studied ontologies has not been a central focus of this year's effort, we expect it to be an area where the investigated ontologies may provide great benefit.

With regards to the question of who will write ontologies it is our guess that some domain experts may be willing and able to become conversant in the language of an ontological system provided that they can see a clear benefit. Some manufacturing domain experts have tackled the equally challenging task of learning STEP technology and the EXPRESS language.

2.2.3 INDUSTRIAL INFORMATION INFRASTRUCTURE

Distributed objects, agents, integrated workflow and supply chains are common themes emerging in the development of an industrial information infrastructure. This mode of operation emphasizes ad hoc access to objects. This is in contrast to the more traditional approach of organizing systems around the semantics of a shared database. The emerging architecture suggests that ad hoc access to shared meta-data and terminology might also prove useful in future information systems. If this turns out to be true, then technology such as the investigated ontologies may prove to be essential in supplying a terminology and meta-data in computational form.

2.3 SUMMARY

Assessing the value of ontologies (or any other technology) to the problem of communicating manufacturing information is, in part, a matter of determining whether it is the simplest possible means to establish a context on exchanged data under which valid inferences (and thus expected behaviors) can be achieved.

The investigated ontologies provide seamless access to its meta-data and ground terms in a computational, formal form. However, one cannot say absolutely whether seamless systems with access to meta-data and possessing a theory of ground are better or worse designs because they possess these attributes. Many very successful, high-performance systems will continue to possess seams, no theory of ground and no access to meta-level information. The genius of design is in part in making the right choice with respect to how context is established and used in communication.

The investigated ontologies can contribute significantly to the alignment of consensus domain terminology.

3.0 Approach and Major Findings for Manufacturing Analysis

A systematic approach was taken throughout this project to ensure that a proper cross-section of manufacturing-related ontological systems were chosen, appropriate analysis criteria was determined, and a proper analysis was performed. The project started by doing a literature survey to determine what appropriate ontological systems were available. This survey included a thorough search of the web and numerous interactions with colleagues in the ontology field. From this survey, the following ontological systems were identified:

- ANSI Ad Hoc Group on Ontology Standards Representation
- CYC
- Enterprise Ontology
- LOOM
- MikroKosmos
- Ontolingua

- Sensus
- SPAR (Shared Planning and Activity Representation)
- STEP (Standard for the Exchange of Product Model Data)
- TOVE (Toronto Virtual Enterprise)
- Wordnet

We then performed a high-level analysis of each of the above ontological systems and eliminated a few due to their lack of appropriateness to this project. In general, the project analyzed these ontologies against the following three criteria:

- the ontology's ability to represent manufacturing information,
- the amount of manufacturing information that was already represented in the ontology,
- the ability for the ontology to inference over the information represented.

The following systems were excluded from the analysis, along with the respective reason:

- ANSI Ad Hoc Committee on Ontology Standards – at the time the analysis was performed, this ontology was not mature enough to properly analyze. In addition, since the upper level of CYC was to be merged with this ontology, an analysis of CYC would be sufficient to also analyze this ontology.
- Sensus – only a taxonomy of terms without definitions were provided and the concepts represented in this system had already been merged with CYC through the Ad Hoc Group on Ontology Standards work
- SPAR – at the time this analysis was performed, it was not mature enough to analyze
- STEP – it was too limited in domain (only product data), there were no formal definitions of concepts, and from the project participants' previous work with STEP, we know it would not be appropriate
- Wordnet – it is more of an on-line super-dictionary than a knowledge base

Once the ontological systems to be analyzed were determined, we moved on to determining the appropriate analysis criteria. There were two approaches suggested, described below:

1. Base our analysis on a matrix on which various manufacturing-related fields would be along the y-axis (e.g. process planning, scheduling, machine capabilities, etc.) and general areas of interest would be along the x-axis (temporal issues, model issues, and material existence issues). In each cell, there would be an appropriate question that would be posed to the ontological system pertaining to its location along the x- and y-axis and the analysis would involve gauging how well the system could answer that question.
2. Base our analysis on typical manufacturing scenarios. This would involve identifying appropriate manufacturing scenarios, extracting the concepts inherent to that scenario, grouping the concepts into appropriate categories, and developing inferencing questions that are based on those concepts. We would then see how well existing ontological systems could model those concepts and determine how well they could answer questions pertaining to those concepts.

The project decided to go with the second approach because it seemed to provide a more complete and accurate analysis than the first. The CAMILE "Factory from Hell" scenario [CAMI91] was identified as an appropriate scenario for our manufacturing analysis. This scenario was developed by Ken McKay as part of an assignment through CAM-I. The scenario details a fictitious factory (based heavily on knowledge gained through site visits to actual factories) including information on many departments and the decision making processes which occur throughout the development of a product. The concepts, which were detailed in the scenario, were extracted and grouped into manufacturing-related categories. The chosen categories were (in no particular order):

- a) Penalties
- b) Costs
- c) Financials
- d) Scheduling
- e) Process Planning
- f) Product Configuration

- g) Resource Planning
- h) Resources
- i) Inventory
- j) Batches/Lots
- k) Orders
- l) Customer/Vendor
- m) Scrap/Rework
- n) Manufacturing Execution

Using these categories and the concepts in each category, we initially examined each of the ontological systems to determine how well they could represent those concepts. Namely, we rated each ontology with respect to the following four categories:

1. Required concepts are not represented in ontology. Related information infrastructure is not available and must be modeled before concepts can be represented.
2. Required concepts are not represented in ontology. Related infrastructural concepts are available. Modeling of required concepts could take place primarily by combination of existing concepts.
3. Representation of required concepts could be achieved through specialization or minor modification of existing concepts.
4. Required concepts are available in ontology and would require either trivial modifications or none at all.

During the initial phases of this analysis, it was found that a few other ontologies were not appropriate for further analysis for the reasons described below.

- LOOM – it is a language and environment. It is not an ontology itself but is quite suitable for implementation of projects using ontologies. Therefore, LOOM would not be appropriate for the development and modeling of a manufacturing ontology.
- MikroKOSMOS – its purpose is to provide a general mechanism for mapping meaning between languages. As such, it has been developed with different capabilities and design structure than would be needed for a manufacturing ontology. Specifically, Mikrokosmos provides no inferencing capability to answer questions that are not explicitly answered in the knowledge base.
- Ontolingua – it is an ontology authoring tool and not an ontology itself. Since this body of work is a development environment, it is not appropriate to attempt to evaluate its direct applicability to manufacturing.

For the above reasons, these ontologies were not further analyzed.

The remaining three ontologies, CYC, Enterprise Ontology, and TOVE, were then analyzed in further detail. The results of this analysis showed that all three packages were approximately equally able to represent manufacturing information (see Appendix A). However, the inferencing capabilities in CYC seemed a bit more mature than the other two packages analyzed. Also, the close relationship that NIST and the ATP Ontology project have with Cycorp would allow the project to more easily leverage Cycorp staff's expertise while modeling the manufacturing ontology. For these reasons, the project decided to proceed with CYC to model the manufacturing ontology.

The one main concern was the fact that we would use a proprietary software package to model information that is meant to be in the public domain. This concern was alleviated because of the following:

1. The upper ontology of CYC is currently exactly the same as the ANSI Ad Hoc Group for Ontology Standards' ontology (which can be represented in KIF or the CycL language). Because there is a bi-directional mapping and translators from CycL to KIF, if necessary, any work modeled in CycL can be easily converted to KIF. The CycL language is currently publicly available.
2. Through an agreement with Cycorp, any concepts that are needed to model manufacturing information in CYC, but which are not currently in the public domain, will be made publicly available.
3. There is currently work in progress in academia to develop an inferencing engine that will work on the CycL language. If this work continues to completion, there should be no concerns on having to use

Cycorp's proprietary inference engine to be able to inference over the information in the manufacturing ontology.

Inferencing capabilities of the various packages analyzed are discussed in Section 5.2.

4.0 Manufacturing Ontological Systems Investigated

The following table summarized the major points related to the ontologies that were investigated. A more detailed description of each of these ontologies can be found in the subsections below.

Ontology	Domain	Purpose	Provides Inferencing?	Development Framework or Full Ontology
ANSI Ad Hoc Group on Ontology Standards	Generic	To merge the upper level ontologies of many of the well known ontological systems	No (although supporting systems may provide inferencing)	Full ontology
CYC	Generic	Enable common sense reasoning about the world	Yes	Full ontology
Enterprise Ontology	Business enterprise and organization modeling	Comprehensive ontology whose main groupings consist of activities, organization, strategy, marketing, and time.	No	Full Ontology
LOOM	Generic	A language and environment for constructing intelligent applications	Yes (forward, truth maintenance)	Development Framework
Mikro-KOSMOS	Knowledge-based translation of natural language	Translate natural language text from one language to another via a language-neutral text meaning representation	No	Full Ontology
Ontolingua	Generic	Development environment and authoring tool for the creation of modular, reusable ontologies.	No	Development Framework
TOVE	Enterprise integration	Provide a generic, reusable data model including shared terminology and meaning that each agent can jointly understand and use	Yes	Full Ontology

Table 1: Summary of Ontologies Investigated

4.1 ANSI Ad Hoc Committee on Ontology Standards

The goal of the ANSI Ad Hoc Group [ANSI98] (associated with the ANSI X3T2 committee on Ontology Standards) is to merge the upper level ontologies of many of the well-known ontological systems (CYC, Pangloss, Penman, Wordnet, etc.). An "upper level ontology" is an ontology of the most general conceptual categories. There are a number of such ontologies out in the world that have proved very useful in natural language processing and other AI oriented applications, as well as in enterprise modeling and database integration. The challenge is that it is difficult to translate between these applications because of the differences in their upper level ontologies. The purpose of the standard will be to provide a sort of ontological baseline to support translation and integration between ontology-based applications, and hopefully also to serve as the starting point for future upper level ontologies.

Included in this group are most of the top names in ontology research and development, including Pat Hayes (Univ. of Western Florida), John McCarthy (Stanford University), John Sowa, Fritz Lehmann (Cycorp Inc.), Ed Hovy (University of South Carolina), Peter Simons (University of Leeds and Ontek, Inc.).

At the time the analysis was performed, all that was available from this group was a high level taxonomy of terms without any definition of what the terms meant. It was assumed that the location of any term within the taxonomy was meant to serve as a loose definition of the term. However, because this ontology standard was being adopted by other systems that we were analyzing, such as CYC, the analysis of those other systems would indirectly allow us to analyze the ontology standard. In addition, because those systems provided additional capabilities that the ontology standard alone did not (e.g., inferencing capabilities, formal definitions of terms, user interfaces, etc.), the respective systems would be a more appropriate choice for use to model a manufacturing ontology. For these reasons, this Ontology Standard was not investigated any further.

4.2 CYC

CYC [CYC98] is a very large, multi-contextual knowledge base and inference engine developed by Cycorp. The goal of the CYC project is to construct a foundation of basic "common sense" knowledge--a semantic substrate of terms, rules, and relations--that will enable a variety of knowledge-intensive products and services. CYC is intended to provide a "deep" layer of understanding that can be used by other programs to make them more flexible.

A drawback to CYC is that its level of knowledge is so "deep" as to be unintuitive to all but CYC knowledge experts. Higher-level knowledge is left to application developers. Not surprisingly, there are large gaps in CYC's higher-level KB as it has only been extended to support whatever application was required for its use. Only some aspects of these extensions are publicly available. Manufacturing is not well represented by the KB. Parts of the healthcare area are well covered; however large gaps will remain for the foreseeable future.

The CYC technology is composed of the knowledge base and inference engine, the CycL representation language, interface tools and application modules. Cycorp is currently working on tools to ease the difficulty of adding to the KB.

The CYC KB is divided into "microtheories", each of which is essentially a bundle of assertions that share a common set of assumptions; typically microtheories are focused on a particular domain of knowledge, a particular level of detail, a particular interval in time, etc. The microtheory mechanism allows CYC to independently maintain assertions that are contradictory, and enhances the performance of the CYC system by focusing the inferencing process. At the present time, the CYC KB contains tens of thousands of terms and several dozen hand-entered assertions involving each term.

CycL, the CYC representation language, is a large and flexible knowledge representation language. It is essentially an augmentation of first-order predicate calculus (FOPC), with extensions to handle equality, default reasoning, and some second-order features. (For example, quantification over predicates is allowed in some circumstances, and complete assertions can appear as intentional components of other assertions.)

CycL uses a form of circumscription, includes the unique name assumption, and can make use of the closed world assumption where appropriate.

CYC 's inferencing capabilities are discussed in the Section 5.2.1.

4.3 Enterprise Ontology

The Enterprise Ontology [ENT98] was built as part of the large Enterprise Project at the Artificial Intelligence Applications Institute at the University of Edinburgh, in collaboration with industry partners. The focus of the project is to promote the use of knowledge-based systems in enterprise modeling and organizational support. The result of this initiative was an Enterprise Toolset, one component of which is the Enterprise Ontology.

The Enterprise Ontology is an in-depth ontology, including terminology as well as definitions of and relationships among terms, for support of business enterprise and organizational modeling. The purpose of the ontology is to provide a formal model of an enterprise on which an enterprise modeling framework, methods and tools could be built. The motivation for a formal model is to establish an agreed-upon shared understanding of the content and characteristics of an enterprise.

The Enterprise Ontology is relatively comprehensive and includes over 90 different concept classes and over 60 relations between concepts. The content of the ontology was originally created using natural language, and was then formally modeled in Ontolingua [GRU93] using the Ontolingua ontology development environment [FAR96] described previously.

In order to represent concepts within the Enterprise Ontology itself, a *meta ontology* was developed, which includes more general modeling terms such as entities, relationships, roles, attributes, and so on. Building on these terms, the concepts in the Enterprise ontology are divided into five categories: activities, organization, strategy, marketing and time. Activities are used to capture the concept of actions and doing, and related concepts such as the "doer" of an activity, resources used or produced, and so on. Organization concepts include entities such as people, machines, or corporations, and are used to model an organization's management structure. Strategy concepts involve the idea of planning and purposes. Marketing involves all sorts of concepts relating to sales, prices, vendors, customers, competitors, and so on. Time is used to represent timelines, specific points in time, or intervals of time duration. Of course, there are interactions among the various categories of concepts. For example an activity may take place over an interval of time as part of a plan.

The intent of the Enterprise Ontology is not to model specific types of enterprises, but to provide a general model that is oriented more towards business and organization than towards a specific domain. From the perspective of the evaluation being performed in this paper, the Enterprise Ontology is greatly lacking. Virtually all concepts and terms that are specific to manufacturing enterprises are missing from this enterprise model. However, the Enterprise Ontology is still viewed as a valuable resource because of the infrastructure it provides. The *meta ontology* provides a flexible set of primitives for building concepts, and since manufacturing enterprises are a subset of business enterprises in general, many of those aspects of a manufacturing enterprise that are not manufacturing-specific are present in the existing ontology. For instance, concepts such as resources, people, machines, and plans will have direct applicability within a manufacturing enterprise model. It should be noted that that in most cases, for application to a manufacturing enterprise further specification of concepts existing within the current ontology will be necessary.

4.4 LOOM

"Loom is a language and environment for constructing intelligent applications. The heart of Loom is a knowledge representation system that is used to provide deductive support for the declarative portion of the Loom language. Declarative knowledge in Loom consists of definitions, rules, facts, and default rules. A deductive engine called a classifier utilizes forward-chaining, semantic unification and object-oriented truth

maintenance technologies in order to compile the declarative knowledge into a network designed to efficiently support on-line deductive query processing." [LOOM98]

As this quote makes clear, Loom is a language and environment. It is not an ontology itself but is quite suitable for implementation of projects using ontologies. Loom is written in Common Lisp and the Common Lisp Object System (CLOS) and is easily integrated into Common Lisp programs. The importance of Loom in this study is that it exemplifies the sort of infrastructure that exists to enable development of high-quality knowledge-based systems. Because Loom is not a commercial product (it is the intellectual property of the University of Southern California) there are fewer barriers to its use.

Our exploratory work with Loom suggests that it is easy to use. Although there may be concerns among some about Common Lisp not being a mainstream programming language, the development of a robust Common Lisp-based HTTP server and a CORBA binding to Common Lisp has eased this problem somewhat.

4.5 MikroKOSMOS

The ultimate objective of the Mikrokosmos [MIKRO95] research project is to define a methodology for representing the meaning of text in a language-neutral format called a text meaning representation (TMR). This would provide a mechanism for Knowledge-Based Machine Translation (KBMT) of natural language text from one language to another (via an intermediary translation into a TMR). In pursuit of this goal, researchers at New Mexico State University have conducted a comprehensive study of linguistic and language use phenomena. These phenomena have been encapsulated in various "microtheories" which are united through the control architecture of the KBMT system.

These microtheories assist the KBMT in translating to and from the language-neutral TMR. The TMR is obtained from analysis of the lexical, syntactic, semantic, and pragmatic information in the input text. This information is represented using elements of the ontology. It is important to note that the TMR is also syntax neutral, since different languages have different syntax. As such, the TMR must avoid using (potentially) language-specific terminology, such as tense or clause. The TMR can also include stylistic factors, discourse relations, and speaker attitudes that may be present in natural language text.

The principle objective of the Mikrokosmos project is, unfortunately, not directed at arbitrary queries of a specific knowledge base, but rather, a general mechanism for mapping meaning between languages. As such, it has been developed with different capabilities and design structure than would be needed for a manufacturing ontology. Specifically, Mikrokosmos provides no inferencing capability answering questions that are not explicitly answered in the knowledge base. This capability is vital for providing useful information in a Manufacturing context. The Mikrokosmos ontology contains a wide variety of basic concepts related to manufacturing (e.g., drill, cut, and make), but it has very few detailed concepts that would be helpful for manufacturing. As such, implementing a manufacturing ontology using Mikrokosmos would require the development of tools for inferencing capabilities and general querying of the knowledge base, as well as adding a tremendous number of detailed concepts to the knowledge base.

4.6 Ontolingua

The Ontolingua [ONTO96] ontology development environment, developed at the Stanford University Knowledge Systems Laboratory, consists of a suite of authoring tools for creating and browsing modular, reusable ontologies. The set of tools provides a World Wide Web-based interface for ontology creation, allowing remote ontology creation or browsing of existing ontologies, many of which are available through the server Ontolingua Server at Stanford University.

The Ontolingua ontology development environment provides an extensive framework to support ontology authoring. Ontologies that are developed are modular and reusable, meaning that an ontology can "include" other ontologies and make use of their content simply by including references to them. Thus, when constructing a new ontology, many of the basic kinds of entities and infrastructure are already available by virtue of having been previously created by somebody else. These range from generic

ontologies concerning algebra, time, and standard units, to more specific ontologies such as parametric constraints and mechanical components. Leveraging previous development efforts can result in significant timesaving for new ontology creation.

The Ontolingua ontology development environment models information using the Ontolingua language [GRU93], a language based on the Knowledge Interchange Format (KIF) [GEN92]. Ontolingua expands the basic first-order predicate logic formalism provided by KIF to also include syntax for an object-oriented representation (classes, instances, slots, relations, etc.) In addition to the web-based authoring interfaces, the development environment also provides translation into other knowledge representation languages, including Loom [MAC91], Epikit [GEN90], Generic-Frame [CHA97] and pure KIF.

The purpose of this paper is to evaluate ontologies and not ontology authoring tools. Since this body of work is a development environment, it is not appropriate to attempt to evaluate its direct applicability to manufacturing. However, because of its advantages (ease of use, availability of existing modular ontologies to leverage from, ties to KIF and translator facilities to interface with other knowledge representation languages), this environment would be a strong candidate for consideration if a new manufacturing-related ontology were to be built from scratch. Indeed, this development environment was used to model the Enterprise Ontology, which is one of the ontologies evaluated in this paper.

4.7 TOVE (TOronto Virtual Enterprise)

In order to support enterprise integration, it is necessary that shareable representation of knowledge be available that minimizes ambiguity and maximizes understanding and precision in communication. Secondly, the creation of such a representation should eliminate much of the programming required to answer "simple" common sense questions about the enterprise. The goal of the TOVE [TOVE98] project is to create a generic, reusable data model that has the following characteristics:

- provides a shared terminology for the enterprise that each agent can jointly understand and use,
- defines the meaning of each term (a.k.a. semantics) in a precise and as unambiguous manner as possible,
- implements the semantics in a set of axioms that will enable TOVE to automatically deduce the answer to many "common sense" questions about the enterprise, and
- defines a symbology for depicting a term or the concept constructed thereof in a graphical context.

The TOVE reusable representation represents a significant ontological engineering of industrial concepts. All axioms and definition are specified natively in the Knowledge Interchange Format (KIF) [GEN92]. It also has presentations using the Frame Ontology from the Knowledge Systems Laboratory (KSL) (<http://www.ksl.stanford.edu/>) from Stanford and will shortly have a presentation in XML (eXtensible Markup Language) [XML98].

The work began by translating the ontologies developed at Carnegie Mellon from LISP into a C++ environment. The ontology was then modified and extended. Currently, the ontology spans: activities, state, causality, time, resources, inventory, order requirements, and parts. There has also been work to axiomatize the definitions for portions of our knowledge of activity, state, time, and resources. The axioms are implemented in Prolog and provide for common-sense question answering via deductive query processing. Future work focuses on the development of ontologies and axioms for quality, activity-based costing, and organization structures.

5.0 Discussion of Manufacturing Analysis

Apart from the major findings described in above two sections, there was a couple of other interesting findings, discussed below.

5.1 Context in Ontologies

The main objective of ontology development is to develop a standard vocabulary or to predefine terminology in order to facilitate exchange of information. Ontologies help create a uniform basis for

information exchange by enabling the representation and communication of the meaning of a given term. However, a secondary issue that must be addressed arises when a term has multiple valid definitions. Being able to represent these definitions formally does not solve the problem of knowing which definition to use in a given circumstance.

This problem is being addressed in several ontology development efforts through the use of contexts in ontologies (e.g. [CYC98], [MIKRO95], and [TOVE98]). Context, also referred to in some efforts as microtheories, allows additional information beyond specific formal term definitions to be incorporated into an ontology. This contextual information may be represented implicitly or explicitly within an ontology. In the case of the Ontolingua Ontology Development Environment, modular ontologies are created and combined or included as components of larger ontologies. In one sense, this can be thought of as an implicit representation of context, since a term may be defined one way in one ontology and differently in another. MikroKosmos uses context to help resolve the meaning of words that could have multiple meanings. Although the way they do this is vague (possibly because it provides them with part of their proprietary advantage), it partially involves grammatical rule (e.g., adjectives follow nouns in Spanish, adjectives precede nouns in English). The placement of these words in a sentence provides the context to help to define what the words mean. CYC represents context using "microtheories", each of which is essentially a bundle of assertions that share a common set of assumptions; typically microtheories are focused on a particular domain of knowledge, a particular level of detail, a particular interval in time, etc.

5.2 Inferencing in Ontologies

Inferencing, in general terms, is the ability for a system to deduce new information that is not explicitly represented from concepts that are currently represented in a knowledge base. For example, let's assume that a particular manufacturing process (Process B) must be performed within 24 hours of the completion of another manufacturing process (Process A). In order for a scheduling program to decide when to schedule Process A, it must have access to certain information. Some of this information would be explicitly represented, such as the expected durations of Process A and B, the current time, and the standard hours that the factory is open. However, some of the information necessary is unlikely to be explicitly represented, such as, whether or not the factory is open "tomorrow". This type of information would need to be deduced from information that is explicitly represented, such as, today's date, today's day of the week, scheduling holidays, and factory hours. An inference engine could provide this deductive capability to determine the information needed but not explicitly represented.

In the ontologies investigated, the tools were designed to work with specific representations; namely: 1) inference engines developed by Cycorp Inc. to work on their CycL representation, 2) a deductive engine developed with LOOM to specifically work on the LOOM knowledge representation, and 3) a set of tools developed all around the world to work on information represented in the Knowledge Interchange Format (KIF). The LOOM deductive engine is discussed in Section 4.4. The other two inferencing approaches are discussed below.

5.2.1 Inferencing in CYC

The CYC inference engine utilizes a variety of general logical deduction techniques, including modus ponens, modus tollens, and universal and existential quantification, as well as some specialized AI inferencing mechanisms, such as inheritance and automatic classification.

Because the CYC Knowledge Base (KB) contains hundreds of thousands of assertions, many inferencing mechanisms intended for smaller KBs are too inefficient for use with CYC's large-scale KBs. As a result, the CYC team has been forced to develop other techniques. CYC performs best-first search over proof-space using a set of proprietary heuristics, and uses microtheories to optimize inferencing by restricting search domains. CYC also includes several special-purpose inferencing modules for handling a few specific classes of inference. One such module handles reasoning concerning collection membership/disjointness. Others handle equality reasoning, temporal reasoning, and mathematical reasoning.

5.2.2 Inferencing Using KIF

Although numerous colleagues swear that there currently exist inferencing engines for KIF, none were able to produce a single one. Even a web search should little sign of an engine existing. True, a language called Prolog exists which provides inferencing capabilities for its own representation language, which is a restricted form of KIF, but nothing was found that uses KIF directly. Therefore, we can only conclude that if an inference engine does exist, it is certainly not easy to find.

6.0. Healthcare Ontologies / Unified Medical Language System

6.1. Overview

6.1.1. What is an ontology from a healthcare perspective

Similar to manufacturing, there is a pressing problem in the healthcare field that ontologies could help solve; namely, integration of often isolated healthcare-related representations. In this context and ontology can be viewed in two slightly different ways:

1. As a formal representation of pieces of information (e.g. ontologies for disease classification, nursing diagnosis, drug codes, etc.) that one would need to capture. This is the most common use of the word “ontology” in the healthcare arena (this is similar to the way the term is used within manufacturing in the previous sections) and will be used to mean this definition throughout the rest of the paper.
2. As a framework to help bring together pieces of information into a comprehensive system to provide a central location for all necessary information (e.g., similar to an architecture for an enterprise model in the manufacturing arena).

Ontologies exist in both of these areas, although, not surprising, there are many more ontologies that exist for the former than the latter. The following two sections describe the problems and the solutions in more detail.

6.1.2. Problems which healthcare ontologies are trying to solve

Similar to the manufacturing domain, there are multiple, isolated information models that represent different, but not necessarily orthogonal, subsets of the information needed and used in the healthcare field. Examples of these information models, hereby referred to as healthcare ontologies, are presented and described in Section 6.2. Currently each of these models do very well at capturing the aspects of healthcare field which they were created to represent, but they do usually do not interoperate well with each other. This problem has hindered the possibility of creating an “enterprise model” for healthcare – one that incorporates all aspects of healthcare information into a single framework in which information is easily shared and exchanged among various functions that use that information.

6.1.3. Approaches to solving the problem

There seems to be three distinct, yet non-orthogonal, approaches to solving the integration problem described above. The first deals with the development a representation to serve as an interlingua (a neutral representation) to tie together different representations that generally represent the same types of information. This would allow different companies that represent their information in different proprietary formats to be able to share information by first converting Company A’s proprietary representation into the neutral representation and then converting the neutral representation into Company B’s proprietary representation. An example of this type of representation can be found in LOINC [LOINC98] work described in Section 5.2.8.

The second approach focuses on creating a SINGLE, complete representation of ALL information needed in the healthcare field. By creating a single representation, integration of multiple, smaller representations becomes a non-issue – all of the information one needs already exists as a single source. The disadvantage of this approach is that the benefit of previous work on modeling various aspects of the healthcare field

becomes useless except for providing ideas on how to create the larger healthcare representation. An example of this type of approach is the Read Codes [Read98] work described in Section 6.2.13.

The third approach focuses on developing the framework, or the 'glue', to allow any existing or future representations to easily be integrated with each other. In this approach, there will most likely be an all-encompassing structure in which every representation could have its place. An example of this approach is the Unified Medical Language System (UMLS) [UMLS98] which is described in further detail in section 6.3.

6.2. Related Healthcare Ontological Systems

6.2.1. Arden Syntax

The Arden Syntax for Medical Logic Modules (MLMs) [ARDEN92] is a language for encoding medical knowledge. Each MLM contains sufficient logic to make a single medical decision. MLMs have been used to generate clinical alerts, interpretations, diagnoses, screening for clinical research, quality assurance functions, and administrative support.

With an appropriate computer program (known as an event monitor), MLMs run automatically, generating advice where and when it is needed. For example, one MLM warns physicians when a patient develops new or worsening kidney failure. Strictly speaking, the Arden Syntax is not a code system, but a language in which codes can be embedded. For example, Columbia Presbyterian Medical Center's MLM for epilepsy uses ICD-9 codes [ICD-9-CM97] to recognize the condition.

6.2.2. CPT4 (Current Procedural Terminology, 4th edition)

The Physicians' CPT [CPT498] is a listing of descriptive terms and identifying codes for reporting medical service and procedures performed by physicians. It is published annually by the American Medical Association. In the U.S. CPT-4 is required by most payers for physician billing, and is also required in addition to ICD-9 [ICD-9-CM97] for some technical billing.

The CPT coding scheme starts with six broad categories (Evaluation and Management, Anesthesiology, Surgery, Radiology, Pathology/Laboratory, and Medicine). Within these categories the codes are set out in an order that makes sense for that category. For example, anesthesiology codes are arranged by part of the body (head, neck, thorax, etc.), while medicine codes are arranged generally by specialty (ophthalmology, cardiovascular, pulmonary, etc.).

6.2.3. CYC

CYC [CYC98] is a very large, multi-contextual knowledge base and inference engine developed by Cycorp. The goal of the CYC project is to construct a foundation of basic "common sense" knowledge--a semantic substrate of terms, rules, and relations--that will enable a variety of knowledge-intensive products and services. CYC is intended to provide a "deep" layer of understanding that can be used by other programs to make them more flexible. A more detailed description of the CYC system can be found in Section 4.2.

Although CYC is capable of modeling just about any domain imaginable, a considerable amount of effort has gone into modeling concepts and assertions in the healthcare domain. The Cycorp staff includes experts in various healthcare fields to ensure that the healthcare-related concepts are accurately captured within the CYC system.

6.2.4. DRG (Diagnosis Related Group)

A DRG [DRG98] is a classification of a hospital stay in terms of what was wrong with and what was done for a patient. The DRG classification (one of about 500) is determined by a "grouper" program based on diagnoses and procedures coded in ICD-9 [ICD-9-CM97]), and on patient age, sex, length of stay, and

other factors. The DRG frequently determines the amount of money that will be reimbursed, independently of the charges that the hospital may have incurred.

In the United States, the basic set of DRG codes is those defined for adult Medicare billing. For other patient types and payers - CHAMPUS (Civilian Health and Medical Services of the Uniformed Services), Medicaid, commercial payers for neonate claims, Workmans' Compensation - modified groupers and additional DRG codes are used.

6.2.5. ECRI's Medical Device Codes

ECRI is an independent, non-profit institution that has provided the healthcare community, both nationally and internationally, with information about the safe and efficacious use of medical technology.

ECRI offers a set of codes for identifying medical equipment. The Health Devices Sourcebook, a directory file produced by ECRI, contains current address and marketing information on U.S. and Canadian manufacturers and distributors of more than 4,500 classes of medical devices. The database utilizes ECRI's internationally endorsed Universal Medical Device Nomenclature System (UMDNS) [UMDNS98]. An online thesaurus is available as an aid in locating broader, narrower, and related product names. The file contains three types of records: product (device) records, manufacturer records, and servicer records. International coverage of companies is provided.

6.2.6. ICD-9-CM (International Classification of Diseases, 9th Revision, Clinical Modification)

The ICD-9-CM [ICD-9-CM97] is based on the official version of the World Health Organization's 9th Revision, International Classification of Diseases. ICD-9 is designed for the classification of morbidity and mortality information for statistical purposes and for the indexing of hospital records by disease and operations, for data storage and retrieval. Diagnoses and procedures coded in ICD-9-CM determine the DRG [DRG98] that controls reimbursement by U.S. Public Health Service and Health Care Financing Administration programs, and most other payers.

ICD-9 codes are sometimes criticized as better suited for billing than for categorizing clinical information. The fact remains however that every U.S. hospital's diagnoses and procedures code is in ICD-9-CM. As managed care erases the line between clinical and financial management, increasingly hospitals are mining ICD-coded records for the limited clinical information that may be found there.

6.2.7. ICD-10 (International Classification of Diseases, 10th Revision)

ICD-10 [ICD-1098] is much larger than ICD-9. The number of categories available for the classification is significantly enlarged and further detail is available. The following is a quote from the Centers for Disease Control (CDC) Web site (<http://www.cdc.gov>) on how ICD-10-CM differs from ICD-9: "Notable improvements in the content and format include: the addition of information relevant to ambulatory and managed care encounters; expanded injury codes; the creation of combination diagnosis/symptoms codes to reduce the number of codes needed to fully describe a condition; the addition of a sixth character; incorporation of common 4th and 5th digit sub-classifications; laterality; and greater specificity in code assignment. The new structure will allow further expansion than was possible with ICD-9-CM."

At present ICD-10 is widely used in Europe. In the U.S., however, migration to ICD-10 is complicated by the fact that ICD-9-CM is embedded in hospital billing systems. The U.S. National Center for Health Statistics has developed a timeline recommended by the National Committee on Vital and Health Statistics (NCVHS) to have ICD-10-CM in use for morbidity diagnoses in the year 2001.

6.2.8. IUPAC (International Union of Pure and Applied Chemistry)

IUPAC [IUPAC98] is a voluntary non-governmental, non-profit organization that unites chemists from all over the world. The object of the Union is the advancement of both pure and applied chemistry.

IUPAC grew out of the international recognition of a need for standardization in chemistry, it being accepted that standardization of weights, measures, names and symbols is essential to the well-being and continued success of the scientific enterprise. Indeed, it is essential for the smooth development and growth of international trade and commerce.

It was this desire for international cooperation amongst chemists, and to facilitate the work of the international, but fragmented, chemistry community chemistry that was one of the earliest characteristics of the Union. Indeed, even before the creation of IUPAC (1919), the body out of which the Union developed, International Association of Chemical Societies (IACS), had met in Paris in 1911 and produced a set of proposals for the work that the new Association should address. These included:

- Nomenclature of inorganic and organic chemistry;
- Standardization of atomic weights;
- Standardization of physical constants;
- Editing tables of properties of matter;
- Establishing a commission for the review of work;
- Standardization of the formats of publications;
- Measures required to prevent repetition of the same papers.

6.2.9. LOINC (Logical Observation Identifiers, Names, and Codes)

The LOINC™ [LOINC98] database provides a set of universal names and ID codes for identifying laboratory and clinical observations. The purpose is to facilitate the exchange and pooling of clinical laboratory results, such as blood hemoglobin or serum potassium, for clinical care, outcome management, and research. Currently, many laboratories are using ASTM 1238-94 or its sister standard, HL7, to send laboratory results electronically from producer laboratories to clinical care systems in hospitals. Most laboratories identify tests in these messages by means of their internal (and idiosyncratic) code values, so the receiving systems cannot fully "understand" the results they receive unless they either adopt the producer's laboratory codes (which is impossible if they receive results from multiple source laboratories, e.g.; the hospital lab, the local commercial lab, and a nursing home lab), or invest in work to map each laboratory's code system to the receiver's internal code system.

If laboratories all used the LOINC codes to identify their results in data transmissions, this problem would disappear. The receiving system with LOINC codes in its master vocabulary file would be able to understand and properly file HL7 results messages that also use the LOINC code. Similarly, government agencies would be able to pool results (within limits) for tests from many sites if they were reported electronically using the LOINC codes. The LOINC codes (and names) for test observations should be of interest to hospitals, clinical laboratories, doctors' offices, state health departments, governmental health care providers, third party payers, and organizations responsible for quality assurance and utilization review.

The LOINC codes are not intended to transmit all possible information about a test. They are only intended to identify the test result. Other fields in the message will transmit the identity of the source laboratory and the very detailed specimen information. (For instance, the code may identify a blood culture, but the message source code can be more specific and identify the specimen as "pumped blood".) The level of detail in the LOINC definitions was intended to distinguish tests that are usually distinguished as separate test results within the master file of existing laboratory systems.

6.2.10. MeSH (Medical Subject Headings)

The Medical Subject Headings (MeSH) [MeSH98] comprise National Library of Medicine's controlled vocabulary used for indexing articles, for cataloging books and other holdings, and for searching MeSH-indexed databases.

MeSH terminology provides a consistent way to retrieve information that may use different terminology for the same concepts.

MeSH organizes its concepts in a hierarchical structure so searches for a broad concept may include articles indexed to narrower concepts. This structure also provides an effective way for searchers to browse MeSH in order to find appropriate concepts.

Subject specialists in various areas continually update the MeSH vocabulary. Each year hundreds of new concepts are added and thousands of modifications are made. The 1998 version of MeSH includes more than 18,000 main concepts and over 80,000 cross-references.

6.2.11. NANDA (North American Nursing Diagnosis Association)

NANDA [NANDA94] is a set of nursing diagnoses adopted by the North American Nursing Diagnosis Association. As compared to ICD-9-CM codes [ICD-9-CM97], which describe a disease or injury, NANDA nursing diagnoses describe a patient's reactions to the disease.

NANDA is a compact code set. The printed list takes up three to four pages. It is organized around nine "Human Response Patterns":

- 1.Exchanging
- 2.Communicating
- 3.Relating
- 4.Valuing
- 5.Choosing
- 6.Moving
- 7.Perceiving
- 8.Knowing
- 9.Feeling

Within each pattern, NANDA lists one to four subcategories. For example, under Exchanging, 1.3.2 is "altered urinary elimination," and 1.3.2.1.3 is "urge incontinence."

The American Nurses Association has adopted NANDA as the standard for nursing diagnoses in the U.S. NANDA is included in the National Library of Medicine UMLS Metathesaurus® [UMLS98].

6.2.12. NDC (National Drug Codes)

The National Drug Code (NDC) system [NDC98] identifies pharmaceuticals in great detail, even including the packaging. Its use is required by the U.S. Federal Drug Administration for reporting and it is used in many healthcare information systems. NCPDP (National Council for Prescription Drug Programs) drug transactions use NDC. At the end of 1995 there were over 170,000 NDC codes.

A fundamental weakness of the NDC system is that it has no reliable means to cross-link trade names with generics, or even different packages of the same medication. Multum (<http://www.multum.com>) offers a free database that maps NDC codes to clinically useful categories.

6.2.13. Read Codes

The Read Codes [READ98], developed in Great Britain, are a comprehensive list of terms intended for use by all healthcare professionals to describe the care and treatment of their patients. They enable the capture and retrieval of patient centered information in natural clinical language within computer systems.

The Read Codes cover such topics as occupations, signs and symptoms, investigations, diagnoses, treatments and therapies, drugs and appliances and much more. This enables the recording within the computer system of anything from a summary of the episode of care to potentially a full electronic patient record if desired.

Each term is attached to a unique Read Code that is stored within the computer. This allows storage, retrieval and analysis of data. When the information is returned to the screen, the clinician is presented not with the code, but with the familiar clinical term, which therefore retains its usefulness.

The Read Codes can make patient records easily retrievable. The computerized record structure can be accessed both for individual patient care and for purposes such as running practice functions, and in secondary care crossmapping to ICD-10 [ICD1098].

6.2.14. SNOMED (Systemized Nomenclature of Human and Veterinary Medicine)

SNOMED [SNOMED86] was conceived from the start as a system for representing clinical information. Unlike ICD-9 and CPT4, it is not used for billing in the U.S.

Dr. Roger A. Cote, principal author of SNOMED, contrasts it to ICD [ICD-9-CM97]: while the latter is a classification, SNOMED is a "multi-axial coded medical nomenclature." A number of separate codes, one per axis, might constitute a diagnosis. For example, lung (topographical axis) plus granuloma (morphological axis) plus fever (functional axis) plus myobaterium tuberculosis (etiology axis) might add up to a diagnosis of tuberculosis (disease axis).

SNOMED was introduced in September 1993 and is traceable to its roots in the early 1960s as SNOP – the Systematized Nomenclature for Pathology. The new (current version 3.2) of SNOMED International is a comprehensive, multi-axial nomenclature classification work created for the indexing of the entire medical record, including signs and symptoms, diagnoses, and procedures. Its unique design will allow full integration of all medical information in the electronic medical record into a single data structure.

The most current version (June 1996) contains more than 138,000 terms and term codes in 11 separate Modules. The College of American Pathologists and its SNOMED Editorial Board are committed to providing updates no less frequently than twice each year.

SNOMED International is rapidly being accepted worldwide (it is being translated into 13 languages other than English) as the standard for indexing medical record information. The American Veterinary Medical Association and the American Dental Association have recognized SNOMED's virtues and have adopted/endorsed SNOMED for their use. In addition, the American College of Radiology/National Equipment Manufacturers Association will be using a subset of SNOMED in their Digital Imaging Communications Standard (DICOM).

6.3. UMLS [UMLS98]

6.3.1. Overview

UMLS helps health professionals and researchers retrieve and integrate electronic biomedical information from a variety of sources. It can be used to overcome variations in the way similar concepts are expressed in different sources. This makes it easier for users to link information from patient record systems, bibliographic databases, factual databases, expert systems, etc. The UMLS Knowledge Services can also assist in data creation and indexing applications.

The UMLS includes machine-readable "Knowledge Sources" that can be used by a wide variety of applications programs to compensate for differences in the way concepts are expressed in different machine-readable sources and by different users, to identify the information sources most relevant to a user inquiry. The Metathesaurus contains mappings to MeSH (Medical Subject Headings at the National Library of Medicine) [MeSH98], ICD-9-CM [ICD-9-CM97], SNOMED [SNOMED86], CPT [CPT498], and a number of other coding systems.

6.3.2. Parts of UMLS

There are four UMLS knowledge sources, the Metathesaurus, Semantic Network, SPECIALIST Lexicon, and Information Sources Map. Because the first two knowledge sources are of most interest to this paper, they are described in greater detail below. The latter two knowledge sources are simply described enough to give the reader a taste of what they are for.

6.3.2.1. Metathesaurus

The Metathesaurus contains information about biomedical concepts and terms from many controlled vocabularies and classifications used in patient records, administrative health data, bibliographic and full-text databases and expert systems. It preserves the names, meanings, hierarchical contexts, attributes, and inter-term relationships present in its source vocabularies; adds certain basic information to each concept; and establishes new relationships between terms from different source vocabularies.

The Metathesaurus supplies information that computer programs can use to interpret user inquiries, interact with users to refine their questions, identify which databases contain information relevant to particular inquiries, and convert the users' terms into the vocabulary used by relevant information sources. The scope of the Metathesaurus is determined by the combined scope of its source vocabularies. The Metathesaurus is produced by automated processing of machine-readable versions of its source vocabularies, followed by human review and editing by subject experts. The Metathesaurus is intended primarily for use by system developers, but can also be a useful reference tool for database builders, librarians, and other information professionals.

The Metathesaurus is organized by concept or meaning. Alternate names for the same concept (synonyms, lexical variants, and translations) are linked together. Each Metathesaurus concept has attributes that help to define its meaning, e.g., the semantic type(s) or categories to which it belongs, its position in the hierarchical contexts from various source vocabularies, and, for many concepts, a definition. A number of relationships between different concepts are represented. Some of these relationships are derived from the source vocabularies; others are created during the construction of the Metathesaurus. Most inter-concept relationships in the Metathesaurus link concepts that are similar along some dimension.

6.3.2.2. Semantics Network

The Semantic Network, through its 132 semantic types, provides a consistent categorization of all concepts represented in the UMLS Metathesaurus. The 53 links between the semantic types provide the structure for the Network and represent important relationships in the biomedical domain. All information about specific concepts is found in the Metathesaurus; the Network provides information about the basic semantic types that are assigned to these concepts, and it defines the relationships that may hold between the semantic types.

The Semantic Network serves as an authority for the semantic types that are assigned to concepts in the Metathesaurus and that are assigned to databases in the Information Sources Map (ISM). The Network defines these types, both with textual descriptions and by means of the information inherent in its hierarchies.

The semantic types are the nodes in the Network, and the relationships between them are the links. There are major groupings of semantic types for organisms, anatomical structures, biologic function, chemicals, events, physical objects, and concepts or ideas. The current scope of the UMLS semantic types is broad, allowing for the semantic categorization of a wide range of terminology in multiple domains.

The primary link is the 'isa' link. This establishes the hierarchy of types within the Network and is used for deciding on the most specific semantic type available for assignment to a Metathesaurus concept. In addition, a set of non-hierarchical relations between the types has been identified. These are grouped into five major categories, which are themselves relations: 'physically related to,' 'spatially related to,' 'temporally related to,' 'functionally related to,' and 'conceptually related to.'

6.3.2.3. Specialist Lexicon

The SPECIALIST lexicon is an English language lexicon with many biomedical terms. It has been developed in the context of the SPECIALIST natural language processing project at NLM. The current version includes some 108,000 lexical records, with over 186,000 strings.

The lexicon entry for each word or term records syntactic, morphological, and orthographic information. Lexical entries may be single or multi-word terms. Entries that share their base form and spelling variants, if any, are collected into a single lexical record. The base form is the uninflected form of the lexical item; the singular form in the case of a noun, the infinitive form in the case of a verb, and the positive form in the case of an adjective or adverb.

6.3.2.4. Information Sources Map (ISM)

The problem of identifying appropriate information resources to answer a specific question is as old as librarianship itself. It has gained in complexity with the proliferation of printed and electronic information. The latter, when remotely located, has in the past been accessed mainly via modem-based telephone connections. In recent years, electronic information resources have been increasingly accessed via the rapidly growing global computer communications network known as the Internet, and in particular via the Internet's most popular information retrieval system, World Wide Web (WWW).

The ISM is a database that describes information sources. Software tools being developed in conjunction with the ISM aim to support the following capabilities:

- Determine which information sources are most likely to be relevant to a particular query.
- Supply human-readable information about the scope, probable utility, and access conditions of identified sources.
- Automatically connect to the identified information sources, retrieving and organizing appropriate information.

6.4. Observations

Not surprisingly, the challenge that the healthcare community is trying to tackle through the use of ontologies is not much different than the problems that the manufacturing community is facing; namely, the integration of previously isolated knowledge sources. Another similarity is the way they are trying to use ontologies to solve their problem. The third approach listed in Section 5.1.3, using a single ontological-based architecture to bring together various knowledge sources in an single "enterprise model" (to use manufacturing terminology) is the approach that UMLS is using and which seems to be the most appropriate mechanism for the healthcare community. This seems to be true due to the fact that, in many cases, many pieces of healthcare-related information are necessary to obtain at a given time to aid in making appropriate decisions. This "big picture" of the healthcare field can help to provide all of the pieces of information necessary to facilitate this decision making process.

One difference between the use of ontologies in the healthcare and manufacturing domains is the need for inferencing. It seems that in manufacturing there is a much greater need to be able to deduce new information for existing information as oppose to healthcare in which mainly the clear representation of the information is important. This, of course, could change over time.

7.0 Conclusion/Future Work

Not surprisingly, the analysis of the various ontological systems has shown that there are numerous approaches and methodologies to formally modeling information. Many of these modeling decisions seem to be focused around the intended use of the ontology once created, with very few of these ontologies being created for general use (with the possible exception of the future Ad Hoc Ontology standard [ANSI98]). For this reason, the analysis of these systems with respect to modeling manufacturing information showed that each of these systems offered its own, unique advantages. Because the analysis focused on three main criteria – the ability to represent manufacturing information, the amount of manufacturing information that

was already represented, and the ability to inference over the information represented – the project participants decided to proceed with the CYC system.

With the identification of an appropriate ontology complete, the project will move on to develop a manufacturing taxonomy/ontology using the chosen system. This will involve at least the following three steps:

1. Identification and definition of domain-specific concepts

There have been many efforts to identify semantic concepts in specific domains within manufacturing (e.g., process planning, design, product). The precise definitions of these concepts will be determined and documented to serve as a basis for the ontology described in the next phase.

2. Ontology population

With the knowledge gained from training sessions, work will be performed to model the concepts in the previous phase in the chosen ontological system. At first one domain will be modeled and issues will be tracked and resolved. These lessons learned will then help to guide the modeling of other domains. The output of this work will be the beginning of a domain-specific taxonomy.

3. Domain ontology merging and determination and resolution of semantic mismatches

As work on the ontology creation continues, it is fully expected that there will be conflicting definitions of the same term in different domains. For example, a resource in one domain may be completely different than a resource in another domain. During this phase, these differences will be studied and resolved, possibly through the generalization and/or specialization of necessary concepts. These various domain ontologies will be merged which will result in a common taxonomy.

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Appendix A: Summary of Analysis of Most Promising Ontological Systems

Included in this appendix is a summary of the analyses performed on the most promising ontologies relating to modeling manufacturing information. Each category of manufacturing concepts identified in the analysis criteria (listed in Section 3.0 and repeated below) was given a rating from 1 to 4 (listed in Section 3.0 and repeated below) with respect to each ontology analyzed. A brief explanation for the rating is also provided.

Manufacturing Categories

- a) Penalties
- b) Costs
- c) Financials
- d) Scheduling

- e) Process Planning
- f) Product Configuration
- g) Resource Planning
- h) Resources
- i) Inventory
- j) Batches/Lots
- k) Orders
- l) Customer/Vendor
- m) Scrap/Rework
- n) Manufacturing Execution

Ratings for the Ontology's Ability to Represent Manufacturing Concepts

1. Required concepts are not represented in ontology. Related information infrastructure is not available and must be modeled before concepts can be represented.
2. Required concepts are not represented in ontology. Related infrastructural concepts are available. Modeling of required concepts could take place primarily by combination of existing concepts.
3. Required concepts are not precisely available but related concepts are. Representation of required concepts could be achieved through specialization or minor modification of existing concepts.
4. Required concepts are available in ontology and would require either trivial modifications or none at all.

CYC Analysis

General Comments: In CYC, the philosophy is not to be able to represent a concept with a single predicate or object but rather to be able to do the kinds of reasoning. For instance, there is no object for "addition" but CYC clearly can reason about addition (as well as do addition). In that sense, the idea that representation could be achieved through "minor modification" or "trivial modification" is not necessarily desirable even though that is clearly implied by the proposed categorizations. This is much like the idea that you cannot dissect the human brain in hopes of finding the "Chicago" neuron (or the neuron for whatever concept you're looking for).

a) Penalties

Rating: 4

Comments: CYC understands penalties and the objects to which they might refer such as vendors, customers, products, sales, prices, etc.

b) Cost

Rating: 3

Comments: Cost is understood by CYC. Only trivial additions are necessary for it to apply to concepts such as resources and materials, prices, vendors, customers, sales (which already exist).

c) Financials

Rating: 2

Comments: CYC has no specific concept for financials but appears to be able to do financial reasoning and modeling anyway. Minor additions could prove helpful.

d) Scheduling

Rating: 4

Comments: CYC has an excellent model for scheduling, events, plans, and related concepts.

e) Process Planning

Rating: 3

Comments: Recent work in modeling process planning information and functionality could prove useful.

f) Product Configuration

Rating: 3

Comments: CYC understands products, product features, and markets. Domain-specific information or classification varies highly.

g) Resource Planning

Rating: 3

Comments: Resource allocation and planning seems to have an acceptable infrastructure in CYC. Certain key ideas seem to have no analog but likely (hopefully?) that is my own misunderstanding since the ontology is somewhat opaque here.

h-i) Resources/Inventory

Rating: 3

Comments: CYC has an excellent provision for high-level resource management. CYC does not seem to understand its application to manufacturing so some work is needed on our part.

j) Batches/Lots

Rating: 3

Comments: CYC models these concepts albeit using completely different words than the industrial engineer.

k) Orders

Rating: 4

Comments: CYC has a very thorough model for order-related concepts (including customers, prices, vendors, organizations, etc).

l) Customers/Vendors

Rating: 4

Comments: Same as above (Orders).

m) Scrap/Rework

Rating: 2

Comments: CYC understand the concepts of "throwing something away" and how it might affect the state of the world but rework, recycle, etc all seem to be overlooked by CYC. Still this doesn't look like it should require a lot of "rework".

n) Manufacturing Execution

Rating: 2

Comments: Manufacturing-specific information does not exist. However, the generic infrastructure for things like processes, execution, influence factors, resources, resource allocation, capability, all exist.

Enterprise Ontology Analysis

Notes: very few axioms exist since most axioms would not be general but would be domain specific. Thus, even in the best case, additional information modeling will be required for a specific application such as a model mfg. factory. This will probably be true for most ontologies, unless they have already been developed with a specific application in mind.

a) Penalties

Rating: 2

Comments: Concepts such as vendors, customers, products, sales, prices, etc. already exist within the ontology. Other concepts that would be required as part of the infrastructure to model penalties also exist, such as time (deadlines might influence penalties), activities and execution of activities, events, etc.

b) Cost

Rating: In some cases 3, in some cases 4.

Comments: For costs of the product itself, and possibly costs of resources and materials, prices, vendors, customers, sales, already exist. For more abstract kinds of costs, additional concept modeling may be necessary if those concepts do not exist.

c) Financials

Rating: Same as for b), but in some cases possibly even 2, since financials is much broader than cost.

d) Scheduling

Rating: 4.

Comments: Time, events, execution of events, resources, resource allocation & substitution plans, sub-plans, process specification all exist, influence factors, assumptions, all exist.

e) Process Planning

Rating: Varies from 2 to 4.

Comments: Maybe we should be more precise about what we mean by process planning.

f) Product Configuration

Rating: 1,2.

Comments: Products, features, markets, (market) needs exist. The next level of detail that would allow representation of product structure, more general PDM-type concepts, part classifications does not exist.

g) Resource Planning

Rating: 3,4.

Comments: Planning, resources, resource allocation and substitution, process specification, capability, etc. all exist. Activities exist, but specific activities such as maintenance and repairs do not.

h-i) Resources/Inventory

Rating: 3.

Comments: Basic concepts exist, but specialization is required for this application. Things like fixtures, tooling, material, repairs, etc. do not.

j) Batches/Lots

Rating: 3 with a little 2 thrown in.

Comments: Same as h-i), but some more basic concepts may not be available, such as splitting (for splitting of batches)

k) Orders

Rating: 3 with a little 2 thrown in.

Comments: Customers, prices, vendors, organizations exist. Since this is broader, though, some things may not exist.

l) Customers/Vendors

Rating: 4.

m) Scrap/Rework

Rating: 2.

Comments: Processes, execution, influence factors, etc. exist, but no concepts at the level of detail of scrap, rework, associated causes, part evaluation or testing, etc.

n) Manufacturing Execution

Rating: 3.

Comments: Processes, execution, influence factors, resources, resource allocation, capability, etc. all exist. More specific related concepts do not.

TOVE Analysis

a) Penalties

Rating: 2

Comments: Although concepts such as delays and resource consumption are defined, there are no explicit concepts for penalties.

b) Cost

Rating: 4

Comments: For details on the TOVE Cost Ontology, see “A Cost Ontology for Enterprise Modeling” at <http://www.ie.utoronto.ca/EIL/papers/abstracts/30.html>

c) Financial

Rating: 2

Comments: Work within TOVE has so far concentrated on activity-based costing rather than financial concepts.

d) Scheduling

Rating: 4

Comments: For details on the TOVE Scheduling Ontology, see “Intelligent Scheduling Research Group” at <http://www.ie.utoronto.ca/EIL/Scheduling.html> and “Scheduling Ontology” at <http://www.ie.utoronto.ca/EIL/tove/scheduling.html>. The following concepts are currently not explicitly defined (and hence have a rating of 3):

- Queues
- Priority

e) Process Planning

Rating: 4

Comments: For details on process planning concepts within TOVE, see Material Flow Ontology at <http://www.ie.utoronto.ca/EIL/tove/material.html>.

f) Product Configuration

Rating: 4

Comments: For details on the TOVE Product Ontology, see EIL Publications on Design the papers at <http://www.ie.utoronto.ca/EIL/DITL/design-papers.html>. The following concepts are not currently covered by the TOVE Product Ontology, and hence would have a rating of 2 or 3:

- Effectivity
- "as designed", "as built", "as maintained"

g) Resource Planning

Rating: 4

Comments: For details, see the Resource Ontology <http://www.ie.utoronto.ca/EIL/tove/resource.html> and Material Flow Ontology at <http://www.ie.utoronto.ca/EIL/tove/material.html>. The following concepts are currently not explicitly defined in the TOVE ontologies (and hence have a rating of 3):

- Resource preventative maintenance and repairs
- Resource fixtures and tooling

h) Resources

Rating: 4

Comments: For details, see the Resource Ontology at <http://www.ie.utoronto.ca/EIL/tove/resource.html>. The following concepts are currently not explicitly defined in the TOVE ontologies (and hence have a rating of 3):

- Resource fixtures and tooling

i) Inventory

Rating: 4

Comments: For details, see the Inventory Ontology at <http://www.ie.utoronto.ca/EIL/tove/inventory.html> and the Material Flow Ontology at <http://www.ie.utoronto.ca/EIL/tove/material.html>.

j) Batches/Lots

Rating: 3

Comments: These concepts would be an extension of the Resource and Material Flow Ontologies.

k) Orders

Rating: 4

For details, see the Goals Ontology at <http://www.ie.utoronto.ca/EIL/tove/goals.html>.

l) Customers/Vendors

Rating: 2/3

Comments: The concepts of customer and supplier are defined, but the other concepts in the list (such as synchronization, communication, and meta-issues) are not defined.

m) Scrap/Rework

Rating: 3

Comments: Initial concepts can be found in Henry Kim's work on the Quality Ontology as well as the Material Flow Ontology at <http://www.ie.utoronto.ca/EIL/tove/material.html>.

n) Manufacturing Execution

Rating: 2/4

Comments: Concepts such as tracking, preemption, and iteration are defined (and have a rating of 4), but concepts such as priority, change, and human intervention are not defined (and have a rating of 2).

