

# Discovering Ontologies from Performance Systems

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**Abstract:** There is much diversity in the approaches taken to ontological engineering. A common theme that unites them all is the considerable effort associated with developing and validating ontologies. As a result many approaches include in their goals the ability to reuse and share all or parts of other ontologies as one way of reducing the cost of development. This paper describes an alternative where the goal is not to build large-scale common ontologies but to generate domain-specific ontologies for the purpose of modelling and explaining knowledge that we have acquired without the need for significant analysis or structuring. This paper describes a knowledge acquisition technique, known as ripple-down rules (RDR), that was designed to alleviate the problems contributing to the KA bottleneck and the maintenance of large knowledge based systems. Recently RDR have been combined with Formal Concept Analysis to allow an abstraction hierarchy of concepts contained in the assertional rule-base to be automatically generated and displayed as a concept lattice. Using this technique, higher-level concepts can be made explicit. This paper looks at this work and assesses its value as an ontological representation and suggests that an alternative to engineering ontologies is to discover them.

## 1. Introduction

There is much diversity in the approaches taken to ontological engineering. Some of this diversity is due to the wide range of views of what an ontology is (see the discussion in Guarino 1996). Existing ontologies vary in their goals, content, size, coverage, formalism and implementation (Noy and Hafner 1997). A common theme that unites them all is the considerable effort associated with developing and validating ontologies. As a result many approaches include in their goals the ability to reuse and share all or parts of other ontologies as one way of reducing the cost of development. Another approach is the automatic generation of ontologies (Komori and Yamaguchi 1998). The latter approach is similar to the use of machine learning to address the knowledge acquisition (KA) bottleneck<sup>1</sup>. This paper describes another alternative that is partially based on criticisms (Dreyfus 1985, Heidegger 1962) of the metaphysical assumption which would require objects to be described using an infinitely large number of attributes in order for a computer to determine the relevant facts and how to apply them. Our stand is not quite so

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<sup>1</sup> This term was coined by Feigenbaum and became popular during the time when knowledge acquisition was seen to be essentially knowledge transfer or mining. The work reported in this paper is based on a situated view of cognition and the term “knowledge acquisition bottleneck” is used to express the problems involved with acquiring knowledge from an expert due to such things as tacit knowledge, the subconscious nature of much expertise and the inability of experts to articulate their reasoning.

pessimistic as our goal is not to build large-scale common ontologies but to generate domain-specific ontologies for the purpose of modelling and explaining knowledge that we have acquired without significant prior analysis or structuring.

This paper describes a knowledge acquisition technique, known as ripple-down rules (RDR) (Compton and Jansen 1990), that was designed to alleviate the problems contributing to the KA bottleneck and the maintenance of large knowledge based systems (KBS). It is noteworthy that these are the same issues that have prompted much of the research into ontological engineering and particularly the development of common ontologies, such as ARPA's Knowledge Sharing Effort (Patil, Fikes, Patel-Schneider, McKay, Finen, Gruber and Neches 1992) and CYC (Guha and Lenat 1990). Recently RDR have been combined with Formal Concept Analysis (FCA) (Wille 1982) to allow an abstraction hierarchy of concepts contained in the assertional rule-base to be automatically generated and displayed as a concept lattice. Using this technique, higher-level concepts can be made explicit (Richards and Compton 1997). The approach is simply referred to as MCRDR/FCA. This paper looks at this work and assesses its value as an ontological representation and suggests that an alternative to engineering ontologies is to retrospectively discover them.

## **2. To Engineer or Reverse Engineer**

The retrospective discovery of an ontology or 'explicit specification of a conceptualization' (Gruber 1993) using MCRDR/FCA can be seen as reverse ontological engineering. This analogy holds if we view reverse engineering as the process of uncovering 'secrets' in the original artifact that were not apparent because no design specification was used in the development of the product (Pressman 2000). The development of an MCRDR KBS does not require the user to structure their knowledge, specify relationships between concepts or to provide abstract concepts. The knowledge contained in the MCRDR rules are case-based. Rules are acquired directly from a domain expert who runs an inference on a case and reviews the system-assigned conclusion. If the expert does not agree with the recommendation, they assign a new conclusion to the case and pick some features (attribute-value pairs) in the case, which justify the new conclusion. The conclusion and features become an exception rule to the rule which gave the misclassification. To assist the user and provide online validation, cases which prompt a rule to be added are stored in association with the new rule (these are known as cornerstone cases) and shown to the user when an exception rule needs to be added. The features selected to form the exception rule must distinguish between the current case and the cornerstone case/s for the rule which misfired. This avoids the problem of side-effects which can occur in the maintenance of large rule-based systems (Soloway, Bachant and Jensen 1987). The MCRDR rules provide the "source code" which is used by FCA to develop more abstract concepts and a structure that were not considered during KA. Pressman (2000, p.853) points out that the specification produced using reverse engineering can vary according to the:

- level of abstraction,
- completeness of the documentation,
- directionality of the process
- degree of manual vs automatic effort.

When using MCRDR/FCA to reverse engineer an ontology from a production system, the content of the rules (which is related to the content of the cases) will affect the number of levels of abstraction that may be uncovered. The coverage of the rules for a particular domain will affect the completeness of the ontology. The directionality of the process is typically unidirectional, with all maintenance being performed on the MCRDR rules (Richards and Menzies 1998). However, there is a sense in which the approach is bidirectional. For the purpose of allowing KA in a critiquing mode, the MCRDR/FCA approach allows the user to propose a new rule, have a concept lattice developed which includes the new and other related rules<sup>2</sup>, and to use this information to determine if the new rule fits in with what is currently known about this domain as represented in the knowledge base.

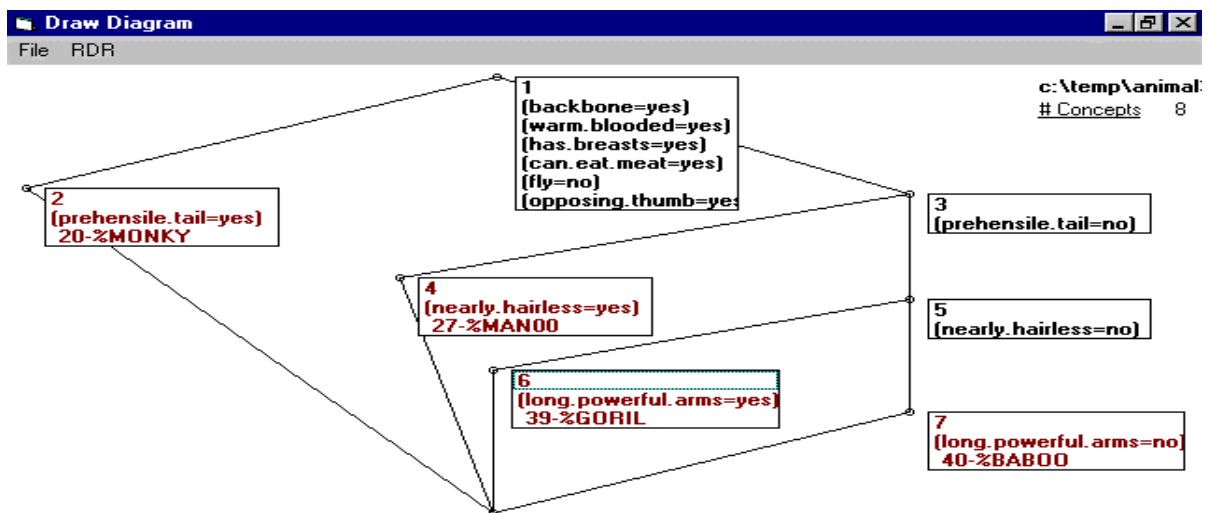


Figure 1: Finding the animals closest to man using MCRDR/FCA on the Animal KBS which were supplied with CLIPS version 5.1.

*A concept in FCA is comprised of a set of objects and the set of attributes associated with those objects. The set of objects forms the extent of the concept and the set of attributes forms the intent of the concept. Labelling has been reduced on the concept lattice for clarity. The intent and extent of a concept are reached by ascending and descending paths, respectively, from that concept. For example, concept number 5 includes the objects: {39-%GORIL (Rule number 39, conclusion=Gorilla), 40-%BABOO (Rule number 40, conclusion=Baboon)} and the attributes: {backbone=yes, warm.blooded=yes, has.breasts=yes, can.eat.meat=yes, fly=no, opposing.thumb=yes, prehensile.tail=no, nearly.hairless=no}. Not surprisingly, the top concept contains the conditions that were used in selecting which rules to view. The monkey is separated the most from man due to the monkey's prehensile tail. The gorilla and baboon are the most similar with the difference being that the gorilla and baboon have body hair and man is nearly hairless. The gorilla and baboon are further differentiated by having long or not long, respectively, arms. If man were classified using the long.powerful.arms attribute it would appear closer to either the gorilla or baboon depending on the attribute value.*

<sup>2</sup> The notion of relatedness will depend on the selection criteria used in restricting which rules to include in a formal context. Richards (2000b) discusses a number of different views that can be selected based on various criteria such as same conclusion, same rule conditions, related rule conditions, bordering values, etc.

Along Pressman's fourth dimension, the current MCRDR/FCA approach is primarily designed to automatically derive an ontology. However, the possibility for human intervention exists. The rule conditions are very low-level or primitive as they are based on the case which prompted them. By finding intersections of shared conditions between rules, FCA uncovers higher concepts. The ability to show higher levels of abstraction than were originally specified means that the lattice does more than just restructure or re-represent the original low-level concepts. The MCRDR/FCA tool allows the user to name a higher-level concept which is stored for future use. The label will be retrieved and displayed on the lattice whenever a concept is generated with the same set of attributes and objects as the named concepts. For example, in Figure 1 the top concept (number 1) includes the higher-level concepts: vertebrate (backbone=yes); mammal (warm.blooded=yes, has.breasts=yes); carnivore (can.eat.meat=yes), primate (opposing.thumb = yes). If this lattice had been generated from concepts covering more than primates the lattice would appear more as a taxonomy of the animal kingdom showing branching just below the top node into backbone=yes and backbone=no. Further branching would occur using attributes which distinguish between the main types of vertebrates and invertebrates. The user may prefer to label these nodes with the appropriate name of the abstraction. Despite the ability to label abstractions, at this stage we do not add a rule to represent the higher concept as the value of doing so is not clear particularly when it raises the issue of performing maintenance in both directions.

You may wonder why we are interested in finding an ontology if we do not need it for KA. The answer lies in the goals of reverse engineering. Since modeling the domain, structured interviews, laddered grids and other KA techniques are not part of the RDR KA process there is virtually no documentation or design plan. Why do we want documentation or a specification ? Because we want to reuse the knowledge, not because it was hard to capture in the first place, but because we want the KBS to provide more than just conclusions. We want to allow the user to explore and interact with the rules in multiple ways. In this way we reuse the knowledge resource, originally captured for inferencing, for such purposes as tutoring, modeling, explanation, critiquing and 'what-if' analysis. Such reuse was limited in MCRDR without FCA since relationships, abstractions and structure were not explicitly captured during the KA process. So while modeling is not a prerequisite for KA, maintenance or inferencing using MCRDR, models of abstraction are beneficial for teaching (Schon 1987) and for explanation (Clancey 1993) types of activities.

Taking a step back from the MCRDR/FCA approach, let us examine further the motivation for reverse engineering. Reverse engineering ontologies can only be a useful approach if the cost of building or obtaining the original source is substantially less than engineering the ontology in the first place. The whole notion of cost-saving using reverse engineering may seem absurd if we view ontologies as a solution to the problem of acquiring knowledge. Many within the KA community see ontologies as a means of obtaining a wealth of structured, and hopefully already validated, knowledge that can be used in the development of KBS. Unfortunately, many of the difficulties associated with the KA bottleneck also hamper ontology acquisition. We seem to have the chicken and egg problem. To alleviate the ontology acquisition bottleneck, there is a strong focus on the sharing and reuse of ontologies. One approach is the development of libraries of reusable ontologies containing components which could be assembled together. However, integration of ontologies is itself seen "as a challenging task" (Noy and Hafner, 1997, p.53). This problem occurs due to the content, partitioning and structure of concepts and the variability in the knowledge

representation (KR) used. Noy and Musen (1999) offer two solutions to the problem of integration: 1. merging multiple ontologies into one; 2. aligning ontologies in a way that allows sharing and reuse of information between them. Another approach to integration is the use of specific principles for the development of a *core ontology* which is part of the library (Valente and Breuker 1996). What seems to be an even bigger impediment to the reusable library of ontologies approach is the *interaction problem* which contests the notion that problem solving knowledge and domain knowledge are two distinct components of a KBS since the domain knowledge needed will be strongly affected by the type of problem and the method of inference (Bylander and Chandrasekaran 1988). None of these approaches are an easy or complete solution to the high cost of developing ontologies. Russ, Valente, MacGregor and Swartout (1999) offer a discussion of the tradeoffs between reusability and usability of ontologies and conclude that current tools do not provide a practical solution. These approaches are founded on the basic assumptions that the cost of KA is higher than the cost of building the ontology and that KA will more easily follow once the ontology is available. While progress is being made on a number of fronts, I wish to challenge these assumptions and consider an alternative approach where ontology building follows KA.

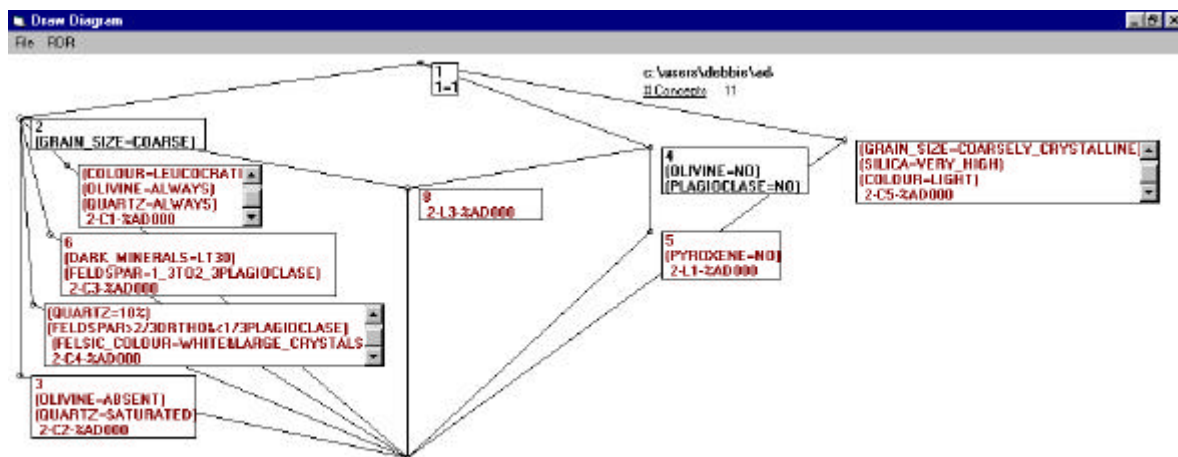


Figure 2: The Concept Lattice for the Conclusion %AD000- Adamellite based on seven knowledge bases (KB)s. The KBs are identified by C1, C2, C3, C4, C5, L1 and L3.

The first assumption to be challenged is that KA is hard. This has not been the experience with building RDR KBS since a 7,000 rule KBS can be directly entered and validated by a domain expert at a speed of one rule per minute (Pacific Knowledge Systems, personal communication). A commercial implementation known as LabWizard (Lazarus 1999) is currently in use in a dozen pathology laboratories. An earlier success is the Pathology Expert Interpretative Reporting System (PEIRS) (Edwards et. al. 1993). RDR have been applied to other domains and problem types and it is our continuing goal to explore the utility of RDR to a full range of problem types (Compton, Ramadan, Preston, Le-Gia, Chellen, Mulholland, Hibbert, Haddad and Kang 1998). Key features of RDR that have assisted easy KA are the use of an exception structure for knowledge representation which allows local patching of knowledge and the use of cases to motivate, assist

and validate the acquisition of new knowledge. Local patching and cases ensure that knowledge is captured and stored in its context.

Since KA is easy the motivation for reuse of knowledge in RDR KB is minimal<sup>3</sup>. The sharing of knowledge has been of interest and has been facilitated by the inclusion of ideas from FCA. The knowledge from multiple MCRDR KBS can automatically and easily be combined and represented as a concept lattice using FCA (Richards and Menzies 1998). An example is given in Figure 2 which shows how knowledge in 7 individual KBS (representing 7 different expert opinions) can be acquired using MCRDR and displayed as a line diagram using FCA. The source of the rule, i.e. the expert, is identified in the object description, which includes the rule number, source and conclusion code. For example, concept number 6 includes the object identified by 2 (rule number), C3 (the C3 expert) and %AD000 (the conclusion code for the rock Adamellite). The seven experts are identified as C1, C2, C3, C4, C5, L1 and L3. See the caption with Figure 1 which explains the nature of a concept in FCA and how to read a concept lattice. The approach has also been applied to assist in the development of a shared body of knowledge in an emergent domain by acquiring expertise from a number of independent agricultural advisors regarding their experience with a newly introduced crop (Richards and Compton 1997). Sharing and integration goes beyond the sharing of knowledge in MCRDR KBS. Work has also been done which looks at the generality of using FCA for creating concept lattices from any propositional KR that can be mapped into a crosstable, known as a formal context. The lattice shown in Figure 1 uses rules from an animal knowledge base shipped with CLIPS 5.1.

The ability to generate a term-subsumption hierarchy using MCRDR/FCA could possibly be used as a framework for comparing and combining existing ontologies similar to the approach proposed by (Weinstein and Birmingham 1999). Any ontology, or part there-of, that can be mapped into a crosstable could be used as input to the conflict identification and reconciliation approach offered in (Richards and Menzies 1998). Multiple ontologies in this format can be combined and compared using a four-state model of comparison (Shaw and Gaines 1988). Where concepts are found to be in a state of correspondence (same concept described using different terminology or in the FCA sense the same object described using different attributes/attribute names) a table can be created which maps terms. The use of mappings is a common (e.g. Gennari, Tu, Rothenfluh and Musen 1994) alternative approach to the use of core ontologies which was suggested above (Valente and Breuker 1996).

The second widely-held assumption is that building an ontology will allow KA to follow more easily. Evidence of this is not easy to obtain since it would be necessary to perform some kind of controlled experiment to verify the hypothesis. In questioning why no *killer* applications of ontologies appear to exist, Uschold (1998) comments “that ontologies will ultimately deliver value ... remains largely a matter of faith”. It is reasonable to believe that the structure and richness of many ontologies will assist in the development of KBS in a similar way to the communication and guidance benefits provided by PSMs (Menzies 1997). It is unclear, however, whether the cost of building the ontology is less than the cost of traditional manual KA techniques. Before further

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<sup>3</sup> Work has been done on the reuse of knowledge in RDR KBS (Richards 2000a) but the type of reuse concerns reusing knowledge for different purposes such as critiquing or tutoring rather than reuse in different applications or domains.

discussion of the ontology bottleneck and comparison to other approaches, which is given in Section 4, it is necessary to describe MCRDR/FCA in more detail.

### 3. The MCRDR/FCA Approach

MCRDR and FCA have been adequately described by numerous others. The purpose of this paper is to offer some discussion of the alternative approach to ontological engineering that is provided in the combination of these techniques. Interested readers are invited to look at (Kang, Compton and Preston 1995) for more about MCRDR and (Wille 1982, 1989, 1992, 1996) for more about FCA. A few introductory remarks regarding the appropriateness of combining the two techniques will be given followed by an example of how the rules in an MCRDR knowledge base can be used by FCA to generate a concept lattice. A more detailed description of how MCRDR KBS are converted into a formal context and then used by FCA to develop a concept hierarchy is given in (Richards and Compton 1997).

RDR and FCA share a number of views including the beliefs that knowledge applies in a context and that KA is a task that is best performed directly by experts. In both approaches KA is reduced to the task of classifying objects (cases) and the identification of the salient features. In FCA, KA begins with the elicitation of a crosstable from which the concepts derived can be used to generate implications. The implications generated are shown to the user who is asked to say whether they agree or disagree with the implication (Wille 1989). If the user does not agree they are asked to offer a counterexample. This study starts from the opposite direction by using the rules in the MCRDR KBS as the input into a formal context. The reason for this is twofold. Firstly the purpose of using FCA was to uncover higher models in rules that had already been acquired using MCRDR. Secondly, it was felt that the RDR approach to KA was probably less demanding for experts than the development of crosstables, the analysis of the generated implications and the offering of counterexamples which is required by the FCA approach to KA .

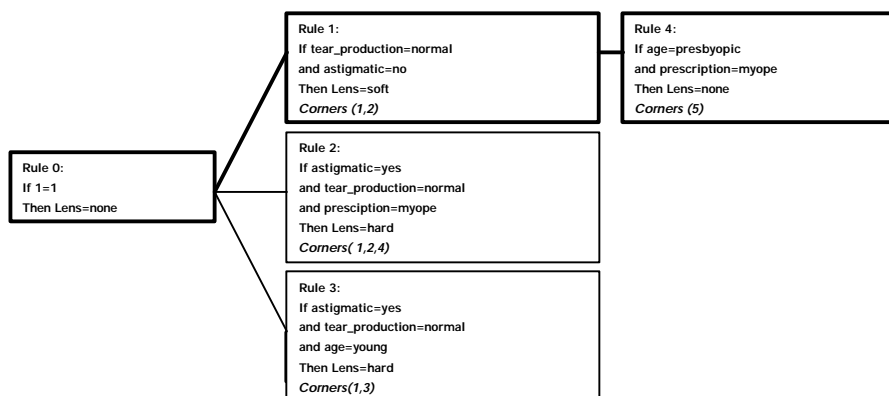


Figure 3. An MCRDR KBS for the Contact Lens Prescription Domain.

The highlighted boxes represent rules that are satisfied for the case {age=presbyopic, prescription=myope, astigmatic=no, tear\_production=normal}. The classification given is Lens=none. As this domain only deals with mutually exclusive conclusions we only get one conclusion, but if the domain was extended to cover spectacles and bifocals then this case could lead to multiple conclusions being given. Since MCRDR relies on cases, the numbers of the cornerstone cases associated with each rule have also been shown in the diagram.

Figure 3 shows the rules in an MCRDR KBS for the Contact Lens Prescription Domain (Cendrowska 1987). Rule 0 is the default rule that will be given as the conclusion if no other rules fire. The branches are exceptions. If a rule is true its children will also be evaluated to see if an earlier conclusion must be overridden by an exception rule. All true rules at the end of pathways are reported as the conclusion.

Figure 4 shows how the rules in Figure 3 are interpreted as a formal context. Each rule is treated as an object and is identified by the rule number and its conclusion code. Each rule condition, which is really an attribute-value pair, is treated as an attribute. This is similar to the technique known as *conceptual scaling* (Ganter and Wille 1989) which has been used to interpret a many-valued context into a (binary) formal context.

	1=1 <sup>4</sup>	astigmatic = no	tear_prod = normal	Age = Presbyopic	Prescription = myope	astigmatic = yes	age = young
0-%LENSN	X						
1-%LENS	X	X	X				
2-%LENSH	X		X		X	X	
3-%LENSH	X		X		X		X
4-%LENSN	X	X	X	X	X		

Figure 4: Formal Context of “MCRDR Contact Lens Rules” in Figure 3.

A set of concepts are derived from the formal context in Figure 4 by treating each row as a concept and generating additional higher level concepts by finding the intersection of sets of attributes and the set of objects that share the set of attributes. For example, objects 1-4 share the attribute: tear\_prod=normal. This forms a new concept as shown in concept 2 in Figure 5. Once all concepts have been found, predecessors and successors are determined using the subsumption relation  $\geq$ . This allows the complete lattice to be drawn. Disjunctions of conditions and negation must be removed to allow the rules to be converted into a binary crosstable. The MCRDR case-based approach to KA results in conditions being captured in conjunctive normal form. Figure 5 shows the concept lattice for the Contact Lens Prescription domain. The diagram shows the importance of the tear\_production=normal concept. We can deduce from the rules that if we see a case where tear\_production=abnormal then the default recommendation of “no lens” will be given. The absence of a condition covering the abnormal state may prompt the user to consider whether the default rule is adequate or whether an alternative or additional recommendation should also be given such as treatment=tear\_duct\_operation. Moving further down the lattice we can see that astigmatic is an important feature that will affect the prescription. If astigmatic=no then a soft lens is recommended, but only when the age=presbyopic and prescription=myope conditions are not true (concept 4 shows the exception rule stated in rule 4). If astigmatic=yes and the prescription=myope or age=young then a hard lens is recommended. While it is true that there is nothing shown in the concept lattice that can not be extracted from reviewing the rules it should be apparent that the relationships between the rule conditions and conclusions are more structured and easily determined in the lattice. As in this example, the increased clarity can be useful in identifying knowledge that is potentially missing.

<sup>4</sup> 1=1 is the condition in the default rule which give the default conclusion as shown in Figure 3.

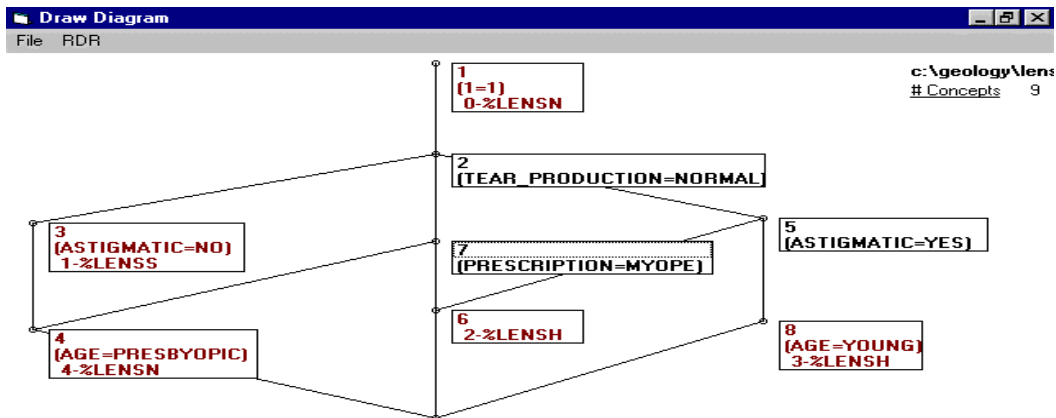


Figure 5: The Diagram Screen in MCRDR/FCA which shows the Concept Lattice for the Formal Context of the MCRDR Contact Lens Rules” given in Figure 3.

## 4. Evaluation and Comparison

In this section we will first look in greater detail at the FCA concept lattice as an ontological and particularly a taxonomic representation and then compare the ontology it represents to those provided by other ontological approaches.

### 4.1 A Closer Look at the FCA Concept Lattice

Ontologies are often equated with taxonomies that can be used to classify categories or concept types in a knowledge base (Sowa 1991). A taxonomy contains a stronger concept of structure and organisation than the word ontology as the word is derived from the Greek *taxis* and *nomos*, which respectively mean arrangement and law. Woods (1991) notes that conceptual taxonomies that allow probabilistic and default rules and abstract and partial definitions may be “useful for indexing and organising information and for managing the resolution of conflicts” (p.45). The line diagram is a complete lattice. Woods remarks that lattices offer “expressive power and the detection and resolution of conflicts in inherited information” (1991, p.80) that otherwise might not have been discovered until runtime. We have sought to harness this power by extending MCRDR/FCA to the domain of requirements engineering (Richards and Menzies 1998). The classification system represented in a taxonomy provides structure that allows new concepts to be positioned. In the FCA framework, any new concept is located based on the description of its *intents* and *extents*, the attributes and objects that describe the concept. In the MCRDR/FCA framework the taxonomy is recreated each time from the specified formal context and each individual concept is ordered in relation to each other concept. Limited default reasoning is supported in the line diagram through the inheritance of properties (attributes) but the use of roles for default reasoning is not well supported as the links or arcs between concepts only specify the subsumes relationships. The work by Priss and Old (1998) which extends FCA to Relational Concept Analysis (RCA) considers relationships other than subsumption will be investigated as a possible means of generating and displaying more kinds of relationships between concepts.

The line diagram can be described as a hybrid system which includes a spatial layout and location system, node based system and a link-based system (Kremer 1998, Lambiotte et. al . 1984). The concept lattice also satisfies the informal definition of a semantic net given by (Shapiro 1991, p.137) as a “labelled directed acyclic graph (DAG) in which nodes represent entities and labelled arcs represent binary relations between entities”. In FCA only the nodes are labelled. While in the theory the edges represent set inclusion, in the interpretation of the formal context the edges may represent a number of different types of relationships. Most of the edges in the concept lattice can be interpreted as is-a links but some edges may refer to other relations such as consists-of. The nature of the relationship will depend on the nature of the knowledge contained in the KBS. For example, the animal KBS produces a taxonomy of animals where one can say that a dog is-a carnivore, is-a mammal, is-a vertebrate but also that a dog consists-of or has-a number of features such as four legs. This inconsistency in the interpretation of the links in the ontology is also found in some other ontologies such as the one developed by (Dahlgren 1988). In contrast, Unified Medical Language System (UMLS) (Humphreys and Lindberg 1993) includes a semantic network of concepts which are held together by 51 different relations. If the UMLS ontology was accessible to MCRDR/FCA it might be possible to automatically label the nature of the relations between the nodes in the concept lattice. However, even if this were possible the benefit would be restricted to the medical domain since UMLS is domain-specific. Another type of knowledge that is not represented in the MCRDR/FCA approach is process knowledge. The ability of the concept lattice to display process knowledge has not been explored. The absence of such knowledge in work-to-date is due to the fact that the MCRDR KA technique does not capture or require any knowledge of processes.

The use of extensional definitions in FCA can be seen as problematic when we come to describe situations for which there are no real examples (Zalta 1988). However, say that we wanted to compare a horse, zebra and unicorn. There is nothing to stop us describing these three objects in terms of their real or imagined properties in a formal context. FCA is an intensional logic that uses descriptions of the attributes of objects as a means of classifying and ordering objects. Of course, if there were a concept that can not be found in any object, real or hypothetical, it would not be possible to include this concept in our subsumption hierarchy unless the properties of that concept are contained in the intersection of other examples. Another problem, which is not specific to the FCA concept lattice, is that approaches that are limited to words constitute a “grammatical model of cognition” (Clancey 1991, p.251) and do not capture non-verbal conceptualisations or model the perceptual-conceptual learning that occurs when humans attach meanings and reinterpretations to words.

## **4.2 A Comparison to other Approaches**

The ontologies considered in this section fall into two main categories. Some, like MCRDR, FCA and KIF (which is really a language/format for knowledge interchange that ontologies can be written in), offer a particular structure and theory for storing ontologies in general. Other approaches such as PLINIUS and CYC are specific ontologies where the structure has been created to fit the development of the specific ontology. Other dimensions for comparison of ontologies have been suggested by Uschold (1998) which include: purpose; representation languages and paradigms; meaning and formality; subject matter; scale; development type;

conceptual architecture; mechanisms and techniques and implementation platform. Noy and Hafner (1997) have added the dimensions of: domain specificity, ease-of-integration, size, implementation, accessibility, design process, evaluation, characteristics of the taxonomy, internal concept structure and relations between concepts, axioms, inference mechanism, applications and contributions. The previous subsection discussed some of these features with regard to MCRDR/FCA. For comparison of ontology application software, the feature taxonomy developed by (Arpirez Vega, Gomez-Perez, Lozano Tello and Pinto 1998) appears useful. Following the current OO way of thinking, the feature taxonomy breaks the features of a product into three main categories: identifying, descriptive and functional. Identifying includes: about the ontology; about the developers, about the distributors. Descriptive includes: general (e.g. type, subject, purpose); scope; design; requirements; cost and usage. Functional includes: such things as description of tools, documentation quality, training courses, availability of PSMs. However, as it is not the goal of this paper to recommend which ontology software to purchase the following discussion provides a comparison of MCRDR/FCA to other ontological approaches, some of which may not be implemented. This section will focus on the dimensions of purpose, design process, structure and approaches to evaluation.

From a comparison of ten well-known ontologies (Noy and Hafner 1997), a number of project goals have been identified. These goals include: natural language understanding, information retrieval, knowledge sharing and reuse, theoretical investigation, simulation and modelling. The first three goals share a higher goal. Natural language understanding, information retrieval and knowledge sharing and reuse are possible solutions to the KA bottleneck problem. One of the claimed benefits of going through the difficult and possibly tedious task of identifying concepts, their properties and relationships is the insight that this may bring to understanding the current problem or domain. There is no doubt that this is the case but if this task is so onerous it adds another degree of difficulty in solving the problem. The biggest risk is that the original problem becomes less important as the ontology becomes the major focus. Related to the understanding benefit is the promotion of a common understanding among coworkers (Jasper and Uschold 1999). MCRDR/FCA seeks to support common understanding and sharing of terms by allowing individuals (or parties) to keep their own terminology in individual KBS and to find where overlaps and inconsistencies exist by comparing KBs using the concept lattice.

The current use of ontologies in the MCRDR/FCA approach is for the purpose of modeling and to a lesser extent simulation. GenSim (Karp 1993) shares this purpose however their focus is on simulation and prediction of experimental results and GenSim is restricted to the domains of molecular biology and biochemistry. As previously mentioned, the motivation for adding FCA concepts into MCRDR was the desire to provide an interaction environment that catered for a wide range of decision making styles and situations. Other similarly motivated work are Protégé (Puerta, Egar, Tu and Musen 1992) and the work on reusing the knowledge in MYCIN (Buchanan and Shortliffe 1984). MCRDR/FCA seeks to offer a wide range of activities within the one session. Protégé and MYCIN offer different applications for different activities.

A key difference between the ontology developed using FCA and a semantically organised ontology such as WordNet is the use of term subsumption for concept structuring. While WordNet uses a hierarchy of superclasses and subclasses, this hierarchy, known as synsets, is

based upon the sense or meaning of the word. A major problem in KA is the use of different terminology. Ontologies can be seen as a way of identifying and reconciling such differences. An example is UMLS (Humphreys and Lindberg 1993) which was developed as a means of combining different sources and users which use different terminology. The FCA concept lattice also seeks to address this problem by offering an extensional and intensional definition of concepts. For example, if one person refers to their object as a feline and another person refers to the same object as a cat, it should become apparent from the set of attributes shared by these objects that the same object is being described. To reconcile such differences a number of strategies are possible, one of them being the use of a synonym or subsumes tables, as mentioned in Section 2 (Richards and Menzies 1998). Another distinguishing feature between FCA and WordNet, or other lexically-based ontologies, is that FCA does not develop one or more hierarchies which are broken up into nouns, verbs, adjectives, etc. The type of terms which appear in a concept lattice are directly dependent on the type of terms used in the formal context. The Generalized Upper Model (GUM) provides a level of abstraction which is in between lexical knowledge and conceptual knowledge. It may be that some benefit can be achieved by including a lexically-based ontology into the FCA ontology so that semantically equivalent terms can be identified and possibly automatically reconciled. Unlike GUM, which has separate hierarchies for concepts and relationships, the FCA concept lattice combines concepts and relationships into the one structure. From a visual point of view the combination seems to be more comprehensible.

In the study performed by Noy and Hafner (1997) it was found that most of the ten ontologies reviewed used a bottom up approach to ontology design and development. Other alternatives included top-down or middle-out. FCA is clearly a bottom-up approach. A major difference between the ten reviewed ontologies and the MCRDR/FCA approach is the automatic generation of the ontologies using FCA. Other approaches to reducing the manual workload is automatic acquisition of the ontology from natural language texts or to use ontologies to automatically generate KA tools (Puerta et. al. 1992). Eriksson, Ferguson, Shahar and Musen (1999) have found that this results in the separation of the ontology definition and the domain-specific definitions contained in the KA tool. The result is a move in the bottleneck from KA to ontology acquisition. To alleviate this new bottleneck they have proposed the automatic generation of ontology editors to reduce reliance on knowledge engineers to maintain domain-classes.

The use of taxonomies in the organization of ontologies is common (Noy and Hafner 1997). The structure of these taxonomies varies with some approaches having one large taxonomy e.g. CYC, Dahlgren's ontology, Sowa's ontology, GUM, UMLS, GenSim, and noun sysnets in WORDNET, or a number of smaller ontologies e.g. TOVE. In some sense MCRDR/FCA offers both approaches. The user may choose to develop a concept lattice of the whole the KB or a collection of KB or many smaller lattices can be generated based on restricted contexts (or rules subsets). Due to navigating around the lattice and computational complexity issues the latter approach is recommended. The FCA concept lattice is closest to the implicit taxonomy found in PLINIUS that is structured using the subsumption relation. The PLINIUS Project (Van de Vet, Speel and Mars 1994) does not use the hierarchical-axiomatic approach used by most other projects for building ontologies. At a surface-level the construction of the PLINIUS ontology is similar to the FCA technique in that it begins with a set of atomic concepts. Elements of these sets are combined to define other concepts. PLINIUS uses rules in its construction kit for determining sub and

superconcepts rather than term subsumption. PLINIUS is very domain specific and it is not known if it can be extended beyond the domain of chemistry. Although the FCA concept lattices tend to be domain specific this feature is due to the nature of the knowledge contained in the KBS. There is no particular restriction on the domain that they can describe. Two further significant differences are that the FCA concept lattice is automatically generated from the primitive concepts and is able to represent properties belonging to an object.

In addition to containing a taxonomy of concepts, most ontologies include a set of meaningful properties and categories (Noy and Hafner 1997). Some ontologies will allow explicit specification of axioms. This is not possible in an MCRDR KB. The absence of axioms in MCRDR and FCA reflects the strongly held view of knowledge applying within the context of a case or example. MCRDR is able to handle knowledge which goes beyond first-order logic but this knowledge is not always clearly displayed in the concept lattice. For example a default rule will appear as a shared concept higher in the lattice but it is not labeled or otherwise identified as a default. See concept 1 in Figure 5. Similarly, context is handled in MCRDR through its exception structure and the storage of cases which prompt new knowledge to be added. In the current MCRDR/FCA tool, cases associated with a particular node on the lattice may be popped-up and the exception structure can be found in the lattice although it may not be completely obvious (for example, the exception structure is more clearly shown in Figure 4).

The bottom line in determining the value of ontologies must involve evaluation. Gomez-Perez has found “a lack of interest in evaluation issues in the ontological engineering community” (1999, p.1] which has resulted in a number of problems which she elaborates. Of particular interest is her evaluation of taxonomic knowledge. Gomez-Perez notes a number of potential errors which can occur when domain knowledge is structured as a taxonomy in an ontology or knowledge base. These errors include circularity, partition, redundancy, grammatical, semantic and incompleteness errors. A detailed analysis of the errors in the taxonomy represented in the FCA concept lattice is not provided here but a few relevant points will be made. Circularity, partition and redundancy errors will be visually apparent in the concept lattice. For example, if the objects dog and cat appear at the same node (possible redundancy) and as a subconcept (subclass) of mammal it will be necessary to introduce (or remove) an attribute of one of these objects so that the two classes will appear disjointly. The way in which concepts can be modified as a result of an error being detected in their definition through lattice exploration is elaborated in (Richards and Menzies 1998). In this way the concept lattice is being used to identify missing, redundant or incorrect concepts and relationships contained in the knowledge base.

The visual detection of these anomalies will be more difficult, and in some cases almost impossible, on large graphs which can not be fully or clearly displayed on one screen. In this situation it would be better to write verification programs which compare textual descriptions of the concepts. This may imply that the graph is only useful for toy problems. Our approach has been to allow the user to specify what aspects of the KB they wish to focus on and display in a lattice. In the above example, the KB may contain concepts for the whole animal kingdom but if the user selects the rule condition (attribute) domestic=yes the graph would include definitions of cat and dog which would reveal that something was wrong with the current concept definitions. While it would be time consuming and error-prone to try to find all anomalies in such an ad-hoc

fashion, we propose the combined use of verification programs to detect a situation requiring manual inspection of a lattice containing the anomalous concepts. As in the dog-cat example above, verification software may detect that something is possibly wrong but human intervention is necessary to determine how to deal with the problem. The lattice can assist the human by providing a visual aid in understanding the nature of the error and how it can be rectified.

The key difference between the knowledge contained in an RDR knowledge base and represented in the concept lattice and most other ontologies is the scope of the knowledge. Knowledge is highly contextualised in the MCRDR/FCA approach. The cases seen and local patching using exceptions provide the context and constrain the applicability and nature of verification anomalies found. Grammatical errors will occur in the concept lattice since the links between concepts are in the theoretical background just set inclusions and since an object may represent in some models an instance and in other models a class. This ambiguity will also result in semantic errors. For a detailed discussion on the verification and validation of RDR KBS see (Richards and Compton 1999).

TOVE (Gruninger and Fox 1995) was the only ontology studied by (Noy and Hafner 1997) which had performed a formal evaluation. Most evaluation was based on whether the ontology was of value in a practical application. RDR and MCRDR have been evaluated empirically (Edwards, Compton, Malor, Srinivasan and Lazarus 1993) and experimentally (Compton, Preston and Kang 1995). Of greater concern to the approach proposed in this paper is the evaluation of the role and use of FCA ontologies. Some evaluation has been done concerning the value of the concept lattice for explanation, exploring and learning about a domain (Richards 1998). Part of this evaluation involved obtaining four different MCRDR KB from the fields of pathology, agriculture, geology and chemistry. The MCRDR rules were used to develop FCA lattices. The lattices were used by a beginner (level lower than novice) to learn and answer questions about the domain. The knowledge 'learnt' after about 1 hour of generating and browsing the lattices was written down and shown to domain experts who were asked to comment on the validity and value of what had been learnt. In the first 3 domains each expert found that the understanding gained was valid for that domain. Experts from the pathology and agricultural domains were impressed by the depth of understanding which the beginner appeared to have. In the geology and pathology case studies where the beginner and expert were able to interact, the lattices provided a valuable communication channel for discussing key ideas and modifying hypotheses. The rules in the chemistry domain tended to have single conditions which resulted in few intersections between rules and uninteresting lattices so there was very little in terms of higher level concepts, structure or relationships to learn from that knowledge source. While such an experiment is not conclusive it does indicate that the ontologies represented in the concept lattice offers knowledge at a greater depth which extends beyond offering an alternative graphical view of the rules. Look at Figures 3 and 5 again and decide which representation is richer. The work by Predigger (1999) which takes a many-valued context and derives concept graphs which show on the edges the nature of the relationships between the vertices would provide an even richer representation. Just as it is necessary in the MCRDR/FCA approach for a human to initially provide the label for any abstractions uncovered, the nature of the relationship, apart from the subsumes relation, would need to be supplied as this information is not automatically derivable from the KB. As suggested in Section 4.1, if MCRDR/FCA were extended to allow the use of other ontologies such as UMLS

or WordNet it may be possible to automatically label the edges with the relationship type. Integration is not an easy task. Asking the user to supply relationship names could be more efficient and accurate. Another lesser problem is that the labeling of edges will decrease the number of concepts that can be shown before comprehensibility is lost. Increased expressibility in a representation always comes with a cost.

Duineveld, Stoter, Weiden, Kenepa and Benjamins (1999) have recently performed an evaluation of a number of ontological engineering tools. Due to the totally different approach to the development of ontologies using MCRDR/FCA only the general features in (Duineveld et. al. 1999) which relate primarily to the usability of the tool are clearly applicable. Questions such as 2.1 “Is it possible to use multiple-inheritance ?” do not make sense but could possibly be replaced by “How can the tool be modified to capture or show multiple inheritance ?” This mismatch occurs because the ontology derived using MCRDR/FCA depends on the knowledge that has been acquired, which is largely dependent on the cases that have been seen, Nevertheless, it would be useful to look at each of the questions, determine how they could be adapted and compare the features that are available in MCRDR/FCA with other tools for building ontologies. Regrettably this is left as further work.

## **5. Conclusion and Future Work**

The connection between FCA and ontologies has been previously made in the work in Web Analysis and Visualisation Environment (WAVE) (Kent and Neuss 1995) which defines an “ontology as a specification of a concept lattice”. The use of conceptual hierarchies in RDR is not confined to the work presented using FCA. Other work includes Ripple-down rules Oriented Concept Hierarchy System (ROCHS) (Martinez-Bejar, Benjamins, Compton, Preston and Martin-Rubio 1998) which incorporates the use of an ontology to support the acquisition and validation of knowledge and the development of Nested RDR (NRDR) (Beydoun and Hoffmann 1997) which allows hierarchies of RDR trees to be built particularly for the purpose of incrementally acquiring search control knowledge. More recent work on the discovery of class relationships that exist in MCRDR KBS is found in (Suryanto and Compton 2000).

There are a number of ontological approaches such as Uschold and Gruninger (1996) and Fernandez Lopez et. al. (1999) that concurrently perform KA and develop the ontology. The Methontology (Fernandez Lopez, Gomez-Perez, Pazos Sierra and Pazos Sierra 1999) ontology-development process includes specification, acquisition and conceptualization of domain knowledge, integration with existing ontologies, evaluation and automatic implementation into Ontolingua. In such approaches, ontological engineering is not a prerequisite task to KA but a complementary task that can be used to assist and validate the knowledge being acquired. What makes MCRDR/FCA so unusual is that KA does not involve the specification of the user’s conceptual model and the ontology is truly automatic and can only be generated after KA has occurred. Similar to the approach offered by ROCHS, it may be desirable to integrate the MCRDR/FCA approach with another ontology to improve the systematic acquisition of knowledge or to speed up the growth of the KB. However, since RDR is fundamentally an incremental KA technique designed to deal with cases as they occur (and since the current approach results in rapid development anyway) such changes to the approach may be counterproductive.

Automatic generation of an ontology from a rule-base means that there is high fidelity between the two. While the degree of domain specificity of the ontology contained in the concept lattice is dependent on and limited to the knowledge in the knowledge base, this approach avoids the interaction problem as knowledge in an RDR KBS is contextualised. The ontological commitment made is directly related to the cases that have been seen.

It would be interesting and hopefully beneficial to explore the ramifications of ontologies for RDR from a theoretical standpoint. Sowa's ontology is philosophically motivated and seeks to address a number of theoretical issues concerning ontologies. The similarity between Sowa's fundamental principles of ontology design as distinctions, combinations, and constraints (Sowa 1995) is embodied in the FCA set-theoretic approach and the use of difference lists, cornerstone case lists (which identify related cases) and rules in RDR. A key difference between the constraints used by Sowa and those found in MCRDR KBS is that in Sowa's ontology the ontology developer is responsible for identifying logical constraints. In RDR, the use of cases constrains what can be represented in the rules.

While the ontology provided in the FCA concept lattice meets some minimal criteria of what an ontology may be, it is a narrow view of an ontology. Many ontological approaches aim to develop a much richer and more expressive representation. The key question to ask is "how useful is the ontology?" The answer to this question will depend on the purpose of the ontology. In the case of MCRDR/FCA our reason for wanting an ontology is to explore and understand the knowledge in alternative ways and in greater depth. Initial evaluation, mentioned in the previous section, indicates that the lattice does add value to the knowledge source. Further investigations and experiments into enriching the type of ontology developed, such as generating concept graphs instead of concept lattices, should reveal whether the current approach is adequate for our purposes.

There are many open issues in the field of ontological engineering. Until definitive answers are found, alternatives such as that offered by MCRDR/FCA deserve some consideration. The alternative offered is to rapidly acquire knowledge and use that knowledge to automatically reverse engineer an ontology.

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### **References**

- Arpirez Vega, J., Gomez-Perez, A., Lozano Tello, A. and Pinto, H. S (1998) (ONTO)<sup>2</sup>Agent: An ontology-based WWW broker to select ontologies *Proceedings of the ECAI'98 Workshop on Applications of Ontologies and Problem Solving Methods* <http://delicias.dia.fi.upm.es/WORKSHOP/ECAI98/accepted-papers.html>
- Beydoun, G. and Hoffmann, A. (1997) Acquisition of Search Knowledge, In Enric Plaza and Richard Benjamins (eds), *Knowledge Acquisition, Modeling and Management. 10th European Workshop, EKAW'97*, Lecture Notes in Artificial Intelligence 1319, Springer-Verlag, 1-16.

- Buchanan, B.G. and Shortliffe, E.H. (1984) *Rule-Based Expert Systems: The MYCIN Experiments of the Stanford Heuristic Programming Project* Addison-Wesley Publishing Co. Reading, Massachusetts.
- Bylander, T. and Chandrasekaran, B. (1988) Generic Tasks in Knowledge-Based Reasoning: The Right Level of Abstraction for Knowledge Acquisition In B.R. Gaines and J.H. Boose (eds.) *Knowledge Acquisition for Knowledge Based Systems*, Academic Press, London.
- Cendrowska, J. (1987) An algorithm for inducing modular rule. *International Journal of Man-Machine Studies* 27(4) 349-370
- Clancey, W.J., (1991) Book Review - Israel Rosenfield, *The Invention of Memory: A New View of the Brain Artificial Intelligence*, 50:241-284.
- Clancey, W.J., (1993) Situated Action: A Neurological Interpretation Response to Vera and Simon *Cognitive Science*, 17: 87-116.
- Compton, P. and Jansen, R., (1990) A Philosophical Basis for Knowledge Acquisition. *Knowledge Acquisition* 2:2
- Compton, P., Preston, P. and Kang, B. (1995) The Use of Simulated Experts in Evaluating Knowledge Acquisition, *Proceedings 9th Banff Knowledge Acquisition for Knowledge Based Systems Workshop* Banff. Feb 26 - March 3 1995.
- Compton, P., Ramadan, Z., Preston, P., Le-Gia, T. Chellen, V., Mulholland, M. Hibbert, D.B., Haddad, P.R and Kang, B. (1998) A Trade-off Between Domain Knowledge and Problem-Solving Method Power In Gaines, B. and Musen, M. (eds) *Eleventh Workshop on Knowledge Acquisition Modeling and Management (KAW'98)* Banff, Canada, April 18-23, 1998, SRDG Publications, University of Calgary, Calgary, SHARE-7.
- Dahlgren, K. (1988) *Naïve Semantics and Robust Natural Language Understanding* Kluwer Academic, Boston, Massachusetts.
- Dreyfus, H. L. (1985) From Micro-Worlds to Knowledge Representation In J. Haugeland (ed.) *Mind Design* (2nd ed.) MIT Press, Massachusetts, pp. 161-204.
- Duineveld, A. J., Stoter, R., Weiden, M. R., Kenepa, B. and Benjamins, V. R. (1999) WonderTools ? A Comparative Study of Ontological Engineering Tools In *Proceedings of the 12th Workshop on Knowledge Acquisition, Modeling and Management (KAW'99)*, 16-21 October, 1999, Banff.
- Edwards, G., Compton, P., Malor, R., Srinivasan, A. and Lazarus, L. (1993) PEIRS: a Pathologist Maintained Expert System for the Interpretation of Chemical Pathology Reports *Pathology* 25: 27-34.
- Eriksson, H., Ferguson, R. W., Shahar, Y. and Musen, M. A. (1999) Automatic Generation of Ontology Editors In *Proceedings of the 12th Workshop on Knowledge Acquisition, Modeling and Management (KAW'99)*, 16-21 October, 1999, Banff.
- Fernandez Lopez, M., Gomez-Perez, A., Pazos Sierra, A., and Pazos Sierra, J. (1999) Building a Chemical Ontology Using Methontology and the Ontology Design Environment *IEEE Intelligent Systems* 14(1) January/February 1999.
- Ganter, B. and Wille, R. (1989) Conceptual Scaling In *Applications of Combinatorics and Graph Theory to the Biological Sciences* (Ed. F. Roberts) pp:139-167, Springer, New York.
- Gennari, J.H., Tu, S.W., Rothenfluh, T.E. and Musen, M.A. (1994) Mapping Domains to Methods in Support of Reuse *International Journal of Human-Computer Studies* 41:399-424.

- Gomez-Perez, A. (1999) Evaluation of Taxonomic Knowledge in Ontologies and Knowledge Bases In *Proceedings of the 12th Workshop on Knowledge Acquisition, Modeling and Management (KAW'99)*, 16-21 October, 1999, Banff.
- Gruber, T. R., (1993) Toward Principles for the Design of Ontologies Used for Knowledge Sharing *Knowledge Systems Laboratory*, Stanford University.
- Gruninger, M. and Fox, M.S. (1995) Methodology for the Design and Evaluation of Ontologies *Workshop on Basic Ontological Issues in Knowledge Sharing* 19-20 August, Montreal, Quebec.
- Guarino, N. (1996) Understanding, Building and Using Ontologies In N. Gaines and M. Musen (eds), *Proceedings of the 10th Knowledge Acquisition Workshop (KAW'96)* Banff.
- Guha, T.V., and Lenat, D.B. (1990) CYC:A Mid-Term Report *AI Magazine* 11(3):32-59.
- Heidegger, M (1962) *Being and Time* (Translated by John Macquarie and Edward Robinson), Harper and Row, New York.
- Humphreys, B.L. and Lindberg, D. A. (1993) The UMLS Project: Making the Conceptual Connection between Users and the Information They Need *Bulletin of the Medical Library Association* 81(2):170.
- Jasper, R. and Uschold, M. (1999) A Framework for Understanding and Classifying Ontology Applications In *Proceedings of the 12th Workshop on Knowledge Acquisition, Modeling and Management (KAW'99)*, 16-21 October, 1999, Banff.
- Kang, B., Compton, P. and Preston, P (1995) Multiple Classification Ripple Down Rules: Evaluation and Possibilities *Proceedings 9th Banff Knowledge Acquisition for Knowledge Based Systems Workshop* Banff. Feb 26 - March 3 1995, Vol 1: 17.1-17.20.
- Karp, P.D. (1993) A Qualitative Biochemistry and its Application to the Regulation of the Tryptophan Operon In L. Hunter (ed.) *Artificial Intelligence and Molecular Biology* Menlo Park, AAI Press, California: 289-325.
- Kent, R. E. and Neuss, C. (1995) Creating a 3D Web Analysis and Visualization Environment *Computer Networks and ISDN Systems*, 28:109-117.
- Komori, Satoshi and Yamaguchi, Takahira (1998) Interactive Composition of Software Engineering Process Using Ontologies In H. Motoda, R. Mizoguchi, P. Compton and h Liu (eds) *Proceedings of the Pacific Knowledge Acquisition Workshop (PKAW'98)*, Singapore, 22-23rd November 1998, 1-12.
- Kremer, Rob (1998) Visual Languages for Knowledge Representation In Gaines, B. and Musen, M. (eds) *Eleventh Workshop on Knowledge Acquisition Modeling and Management (KAW'98)* Banff, Canada, April 18-23, 1998, VKM-6.
- Lambiotte, J.G., Dansereau, D. F., Cross, D.R. and Reynolds, S.B. (1984) Multirelational Semantic Maps *Educational Psychology Review* 1(4):331-367.
- Martinez-Bejar, R., Benjamins. R., Compton, P., Preston, P. and Martin-Rubio, F. (1998) A Formal Framework to Build Domain Knowledge Ontologies for Ripple-Down Rules-Based Systems. In Gaines, B. and Musen, M. (eds) *Eleventh Workshop on Knowledge Acquisition, Modeling and Management (KAW'98)*, Banff, Alberta, Canada, 18-23 April, 1998, Vol 2:SHARE.13.
- Menzies, T.J. (1997) OO Patterns: Lessons from Expert Systems *Software-Practice and experience* Vol 27 (12) (December 1997): 1457-1478.
- Noy, N. F. and Hafner, C. D. (1997) The State of the Art in Ontology Design: A Survey and Comparative Review *AI Magazine* Fall 1997 18(3): 53 - 74:

- Noy, N. F. and Musen, M. A. (1999) SMART: Automated Support for Ontology Merging and Aligning In *Proceedings of the 12th Workshop on Knowledge Acquisition, Modeling and Management (KAW'99)*, 16-21 October, 1999, Banff.
- Patil, R. S., Fikes, R. E., Patel-Schneider, P. F., McKay, D., Finin, T., Gruber, T. R. and Neches, R., (1992) The DARPA Knowledge Sharing Effort: Progress Report In C. Rich, B. Nebel and Swartout, W., *Principles of Knowledge Representation and Reasoning: Proceedings of the Third International Conference* Cambridge, MA, Morgan Kaufman.
- Predigger, S. (1999) The Lattice of Concept Graphs of a Relationally Scaled Context In W. Tepfenhart and W. Cyre *Proceedings of the 7<sup>th</sup> International Conference on Conceptual Structures; Standards and Practices (ICCS-99)* Blacksburg, VA, USA, July 12-15, LNAI-1640, Springer Verlag, Berlin: 401-414.
- Pressman, R. (2000) 5<sup>th</sup> Edn. *Software Engineering: A Practitioner's Approach* (European Adaptation), McGraw Hill, Berkshire.
- Priss, U. and Old, J. (1998) Information Access through Conceptual Structures and GIS In *Information Access in the Global Information Economy Proceedings of the 61<sup>st</sup> Annual Meeting of ASIS'98* :91-99 also <http://php.indiana.edu/~upriss/papers/asis98.ps>
- Puerta, A. R, Egar, J.W., Tu, S.W. and Musen, M.A. (1992) A Multiple Method Knowledge Acquisition Shell for Automatic Generation of Knowledge Acquisition Tools *Knowledge Acquisition* 4(2).
- Richards, D. (1998) The Reuse of Knowledge in Ripple Down Rules Knowledge Bases Systems, *PhD Thesis*, University of New South Wales.
- Richards. D (2000a) The Reuse of Knowledge: A User-Centered Approach, *International Journal of Human Computer Systems* 52 (3) March 2000: 553-579.
- Richards, D. (2000b) The Visualisation of Multiple Views to Support Knowledge Reuse *Intelligent Information Processing (IIP'2000)* An international conference in conjunction with the 16<sup>th</sup> IFIP World Computer Congress WCC2000, August 21-25, 2000, Beijing, China (to appear).
- Richards, D. and Compton, P. (1997) Uncovering the Conceptual Models in Ripple Down Rules In Dickson Lukose, Harry Delugach, Marry Keeler, Leroy Searle, and John F. Sowa, (eds) (1997), *Conceptual Structures: Fulfilling Peirce's Dream, Proceedings of the Fifth International Conference on Conceptual Structures (ICCS'97)*, August 3 - 8, University of Washington, Seattle, USA, Lecture Notes in Artificial Intelligence, Number 1257, Springer Verlag, Berlin, 198-212.
- Richards. D and Compton, P. (1999) An Alternative Verification and Validation Technique for an Alternative Knowledge Representation and Acquisition Technique, *Journal of Knowledge Based Systems* 12 (1999) 55-73.
- Richards, D. and Menzies, T. (1998) Extending the SISYPHUS III Experiment from a Knowledge Engineering to a Requirements Engineering Task In Gaines, B. and Musen, M. (eds) *11th Workshop on Knowledge Acquisition, Modeling and Management (KAW'98)*, Banff, Canada, SRDG Publications, Departments of Computer Science, University of Calgary, Calgary, Canada, Vol 1:SIS-6.
- Russ, T., Valente, A., MacGregor, R. and Swartout, W. (1999) Practical Experiences in Trading Off Ontology Usability and Reusability In *Proceedings of the 12th Workshop on Knowledge Acquisition, Modeling and Management (KAW'99)*, 16-21 October, 1999, Banff.
- Schon, D.A. (1987) *Educating the Reflective Practitioner* Jossey-Bass, San Francisco, CA.

- Shapiro, S. C. (1991) Cables, Paths, And “subconscious” Reasoning in Propositional Semantic Networks In John Sowa (ed) *Principles of Semantic Networks: Explorations in the Representation of Knowledge* Morgan Kaufmann Publishers, Inc. California, 137-156.
- Shaw, M.L.G. and Gaines, B.R., (1988) A Methodology for Recognising Consensus, Correspondence, Conflict and Contrast in a Knowledge Acquisition System in *Proceedings of the 3rd Knowledge Acquisition for Knowledge-Based Systems Workshop*, November 1988, Banff, Canada.
- Soloway, E, Bachant, J. and Jensen, K. (1987) Assessing the Maintainability of XCON-in-RIME: Coping with Problems of a very Large Rule Base *Proceedings of the Sixth International Conference on Artificial Intelligence*, Seattle, WA: Morgan Kaufman, Vol 2:824-829.
- Sowa, J.F. (1991) Toward the Expressive Power of Natural Language In John Sowa (ed) *Principles of Semantic Networks: Explorations in the Representation of Knowledge* Morgan Kaufmann Publishers Inc. California, 157-190.
- Sowa, J. F. (1995) Top-Level Ontological Categories *International Journal of Human-Computer Studies* 43(5-6): 669-685.
- Suryanto, H. and Compton, P. (2000) Discovery of Class Relations in Exception Structured Knowledge Bases In *Proceedings of the 8<sup>th</sup> International Conference on Conceptual Structures; Logical, Linguistic and Computational Issues (ICCS-2000)* Darmstadt, Germany, 14-18 August, Springer Verlag, Berlin (to appear).
- Uschold, M. and Gruninger, M. (1996) Ontologies: Principles, Methods and Applications. *Knowledge Engineering Review* 11(2):93-155.
- Uschold, M. (1998) Where are the Killer Apps ? *Proceedings of the ECAI'98 Workshop on Applications of Ontologies and Problem Solving Methods* <http://delicias.dia.fi.upm.es/WORKSHOP/ECAI98/accepted-papers.html>
- Valente, A. and Breuker, J. (1996) Towards Principled Core Ontologies In B.Gaines and M. Musen (eds.) *Proceedings of the 10th Workshop on Knowledge Acquisition, Modeling and Management (KAW'99)*, Banff.
- Van de Vet, P. E., Speel, P. -H. and Mars, N.J. (1994) The PLINIUS Ontology of Ceramic Materials. Eleventh European Conference on Artificial Intelligence (ECAI'94) *Workshop on Comparison of Implemented Ontologies*, 8-12 August, Amsterdam, The Netherlands.
- Weinstein, P. and Birmingham, W. P. (1999) Comparing Concepts in Differentiated Ontologies In *Proceedings of the 12th Workshop on Knowledge Acquisition, Modeling and Management (KAW'99)*, 16-21 October, 1999, Banff.
- Wille, R. (1982) Restructuring Lattice Theory: An Approach Based on Hierarchies of Concepts In *Ordered Sets* (Ed. Rival) pp:445-470, Reidel, Dordrecht, Boston.
- Wille, R. (1989) Knowledge Acquisition by Methods of Formal Concept Analysis In *Data Analysis, Learning Symbolic and Numeric Knowledge* (Ed. E. Diday) pp:365-380, Nova Science Pub., New York.
- Wille, R. (1992) Concept Lattices and Conceptual Knowledge Systems *Computers Math. Applic.* (23) 6-9: 493-515.
- Wille, R. (1996) Conceptual Structures of Multicontexts In P.Eklund, G. Ellis and G. Mann (eds) *Conceptual Structures: Knowledge Representation as Interlingua* *Proceedings of the 4th International Conference on Conceptual Structures*, LNAI 987, Springer. Verlag, 23-39.

- Woods, W.A. (1991) Understanding Subsumption and Taxonomy: A Framework for Progress In John Sowa (ed) *Principles of Semantic Networks: Explorations in the Representation of Knowledge* Morgan Kaufmann Publishers, Inc. California, 45-94.
- Zalta, E.N. (1988) *Intensional Logic and the Metaphysics of Intentionality*, Cambridge, Massachusetts, MIT Press.