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Situation Analysis for Knowledge-Based Systems

ITQ # CRS 9061

Submitted to the TEM Alternatives Task Force

By

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Summary

Knowledge-based Systems and Knowledge Management

The term *knowledge-based systems*, generally refers to expert system approaches to prediction or decision support. In reality, knowledge-based systems include all predictive and decision support models. The growing recognition of the need to integrate, manage, and share knowledge has led to the emergence of the new “magic bullet” called knowledge management. The “new” knowledge management paradigm proposes to capture informal knowledge based on personal experience and learning, and to integrate it with more discipline or domain specific formal knowledge in a knowledge base.

The current situation

The term *knowledge management* has become popular and we are seeing frequent press references to knowledge management and its importance to the survival of companies in the next millennium. In reality, it is not new. It is, rather, newly popular or perhaps newly understood outside of academic circles. It builds on the successes and failures of data and information management activities and applications. Knowledge management is part of the continuum of data → information → knowledge → wisdom.

Knowledge management research is expanding the tools available for knowledge capture beyond traditional empirical, process, and expert systems approaches. Knowledge management, like data and information management, consists of the following: creating, updating, retrieving, deleting, and archiving[1]. Knowledge management should allow simple, yet powerful access to knowledge for update and use (via reasoning). It should take into account differences among users and among requirements for different problem-solving tasks. The key to effective knowledge management is the representational model used to store and access knowledge resident in the knowledge base.

The field of knowledge management is highly volatile and its similarity to data management activities during the 1970’s and 80’s is both striking and understandable. Similar to the way many organizations were storing data in the 1970’s, many organizations are already practicing elements of what is now known as knowledge management but they are doing so in an uncoordinated and frequently *ad hoc* manner. There is a growing recognition of the need for and value of knowledge sharing and reuse between and within systems and organizations. However, just as the major impediments to data integration were inconsistent or incompatible concepts, definitions, terminology, structures, and formats, the major impediments to knowledge integration will be inconsistent or incompatible concepts, definitions, terminology, structures, and formats. Unfortunately, the standards and protocols to enable such sharing and reuse are only just emerging.

Conclusions

The issue of knowledge management will become increasingly important. It is important to find a balance between planning for and facilitating knowledge integration and unduly constraining research and application testing of valuable knowledge-based applications. It is feasible to develop a knowledge structure that could be used to document and allow the exchange of all the knowledge structures reviewed in this report. To function as a knowledge repository, this structure would

[1] Archiving a knowledge base should not be confused with backing up a knowledge base. Archiving implies a software independent format with complete schemas and dictionaries to allow recovery of the knowledge independent of the original software used to create and manage the knowledge base.

require a set of utilities to import and export the various knowledge structures extant and evolving. Such a system, while having the advantage of storing the contents of multiple knowledge bases would not constitute the vision of integrated knowledge bases implicit in current writings. To meet this vision, we also require the following knowledge-specific components:

- consistent and widely accepted knowledge models (ontologies)
- consistent and widely accepted knowledge structures (schemas)
- consistent and widely accepted knowledge manipulation languages, which will in turn require:
  - a consistent and widely accepted knowledge dictionary
  - a consistent and widely accepted knowledge syntax
  - consistent and widely accepted inference mechanisms

The predictive ecosystem mapping (PEM) knowledge structures used in British Columbia represent a small component of possible approaches to PEM. The establishment of knowledge-structure and knowledge-exchange standards at this time would prove counter productive and restrictive. The standards would also be obsolete before completion. However, we can minimize the pain associated with integrating knowledge bases when the need arises. To do so, we need to plan for eventual knowledge exchange, work to coordinate our efforts, and most importantly document our current and evolving knowledge bases.

In particular, we can document, against a generic knowledge structure, the concepts, processes and mechanisms presumed to produce the ecosystems represented in Terrestrial Ecosystem Mapping (TEM) and predicted in PEM. This ontology of Terrestrial Ecosystem Mapping could be developed in the knowledge repository described above. The ontology should encompass the inputs to predictive ecosystem mapping (e.g., forest cover, vegetation, bioterrain, and soil).

Recommendations

The following recommendations come from understanding of the history and problems associated with database management. It would be fair to say that the problem of integrating knowledge bases will be an order of magnitude greater than that of integrating databases. It is instructive to note that most organizations have yet to successfully integrate their disparate databases.

1. Define Limited Scope for Future Work

The issue of corporate knowledge management, while comparable to corporate data and information management, is significantly more complex and larger in scope. The Resources Inventory Committee (RIC) should carefully consider the scope of knowledge management and determine what if any elements fit within their mandate for standards. The management of inventory-related knowledge-based systems and their supporting databases may be appropriate. Specifically this should include taxonomic models, empirical models, process models, expert systems, and ontological classifications.

2. Conduct Inventory of Knowledge-Based Systems

If standards pertaining to knowledge-based systems and knowledge management are within the mandate for standards, they can be justified on the need for knowledge base and knowledge-based systems integration. A pre-requisite for the development of standards to support integration is an inventory of the knowledge-based systems currently used for inventory-related tasks. The inventory should include:

- the business area and processes supported by each system
- the knowledge products produced and their application
- the type of system, knowledge structures, and inferencing procedures used
- the input requirements and formats

- the level and completeness of supporting data and documentation.

3. Create the BC Ecosystem Ontology

It is important that the concepts, processes, and criteria underlying the ecosystem classification be formally and unambiguously documented in computer retrievable format as a formal ontology. The ontology would identify the dominant processes acting at each level of the classification and the relative contribution of these processes and the mechanisms by which they are presumed to produce the classes identified at each level. The ontology would be structured around the TEM classification system with the processes, balances, and mechanisms documented as relationships between classes at the same level, between levels, and between classes at different levels. The integration of the ontology with a database of class attributes would provide an effective standard for communication, correlation, and quality assurance and quality control of both TEM and PEM mapping..

While the information necessary to construct the ontology exists, it is in the form of internal documents, conference presentations, manuals, and scientific papers. This material should be compiled as a formal ontology in a generic knowledge structure that can be accessed by workers in the field of predictive ecosystem mapping. The ontology could be used to ensure that workers are using the correct ontology, that they are applying it appropriately, and that class attributes are consistent with the ontology. The ontology, not the generic knowledge structure, should be established as TEM and PEM standards.

4. Establish Documentation Standards

Establish a set of documentation and meta-data standards for current and proposed knowledge-based applications. The nature of the documentation will vary depending on the type of knowledge-based system being documented but should include:

- A description of the knowledge structures used. The documentation will vary depending on the knowledge structures used but should include a description of:
    1. Frames (including slots, slot values, etc.) for frame-based systems
    2. Classes (including methods, data structures, etc.) and Objects for object-based systems
    3. Entities and Relations (including membership rules, domains, etc) for relational data-based systems
    4. Column and row definitions together with the method and domain definitions of cells for belief matrix-based systems

    For large knowledge bases, this could be onerous, and an alternative would be examples and automated procedures to produce the descriptions.

- A description of the inferencing processes used including rule bases, decision trees, simulation models, knowledge retrieval algorithms, or processing functions.

5. Provide Coordination

The RIC may wish to consider a coordination role in knowledge management and knowledge-based systems for inventory. This could include organizing annual meetings of practitioners to monitor and encourage knowledge base integration. When the magnitude of knowledge-based systems work warrants, the committee may choose to create a public and private sector working-group on knowledge standards and knowledge exchange.

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1. INTRODUCTION

1.1. CONTEXT

This study is part of a larger initiative being undertaken by the TEM (Terrestrial Ecosystems Mapping) Alternatives Task Force.

The TEM Alternatives Task Force, with representation from the Ministry of Forests and the Ministry of Environment, Lands & Parks (Headquarters and Regions) and the forest industry, was formed subsequent to the November 1997 release of the report “A Business Approach to Terrestrial Ecosystem Mapping (TEM) and TEM Alternatives” by the TEM and TEM Alternatives Project Steering Committee. The objective of the Task Force was to further the development, testing, and documentation of “alternatives to TEM” and Predictive Ecosystem Mapping (PEM) approaches. These tasks were all viewed to be important and necessary precursors for the development of RIC standards regarding the use of predictive ecosystem mapping approaches.

The Task Force undertook an initiative (Evaluation, Role & Development of Standards for Predictive Ecosystem Approaches to Terrestrial Ecosystem Mapping) that is focused principally on Predictive Ecosystem Mapping approaches in terms of the following:

- the continued but more structured evaluation of the approaches
- the future role of the approaches in the TEM inventory program
- the formation of TEM–PEM Principles & Transitionary RIC standards around the use of these approaches

Specific objectives for the initiative to the end of fiscal year 1998–99 and for early 1999-2000 comprised three main components as outlined below. Components A, B4 and C are being undertaken mainly by a Secretariat Team on behalf of the TEM Alternatives Task Force. Components studies B1, B2 and B3 will be coordinated by the Secretariat Team but will otherwise be accomplished using expert consultants in the respective fields.

A. **Direction & Coordination** — to coordinate and create a forum for an integrated TEM and TEM Alternatives program by developing an overarching framework (i.e., a road map), establishing a set of guiding principles and preparing an evolving working “white paper”. These coordinating functions and framework tools will provide overall direction and guidance for managing the TEM Alternatives inventory program during this transition phase.

B. **Detailed Supporting Studies** — to undertake detailed supporting studies, as set out in the framework above (A), that will help to establish a more thorough understanding and foundation for a future TEM and TEM Alternatives inventory program. The following detailed studies are required:

1) *Situation Analysis of Knowledge-Based Systems* in the context of corporate information system directions

2) Problem Analysis on Data Quality Assessment Issues: Inputs, Outputs and Reporting Requirements

3) Problem Analysis on Inventory Reliability, Quality Control, Field and Knowledge Base Validation Procedures

4) Compendium of Predictive Ecosystem Mapping Case Studies

C. **TEM–PEM Principles & Transitionary Standards** — to define a set of TEM–PEM Principles & Transitionary Standards in the context of an evolving and overarching framework (A) and based on the findings of the detailed studies (B1-B4). These principles and transitionary standards will aim to provide a framework for and clarity to the present transitionary circumstances while at the same time offer reasonable flexibility for evolution and innovation.

This study is item B1 above, "Situation Analysis of Knowledge-Based Systems."

1.2. SCOPE

The term *knowledge-based systems* is often construed to mean expert systems. This report expands the concept of knowledge-based systems to include taxonomies and empirical and process or simulation models as well. Knowledge-based systems are discussed in the context of encompassing knowledge management issues since knowledge-based systems represent but one component of the knowledge issue, and knowledge-based systems will ultimately have to be integrated into an overall corporate knowledge management program.

The field of knowledge management is both new and highly volatile. While we were able to find many popular articles on knowledge management and some overviews, all dealt with relatively small subsets of the range of work we found referred to as knowledge management. Unfortunately, we were unable to find a comprehensive overview of the current state and direction of knowledge management. Therefore, much of the effort was placed on understanding the status and direction of knowledge management development under the assumption that knowledge-based systems will ultimately need to be integrated into a larger knowledge management system. This will include such things as patents, documents, manuals, operating procedures, standard practices, and a corporation's informal knowledge of how things are done. The ultimate goal was to identify issues that would increase or mitigate the integration of knowledge-based systems into a corporate knowledge management structure.

1.3. APPROACH

The approach consisted of a review of knowledge-based systems currently implemented in support of predictive ecosystem mapping by the BC Ministry of Environment, Land and Parks, the BC Ministry of Forests, and the private sector. This was followed by a comprehensive review of current literature and World Wide Web sites supporting knowledge research and software development. Some 4000 documents were scanned for relevance or reviewed in detail. In addition, 15 knowledge-based software applications were reviewed either as online demos or as demonstration software.

The review concentrated on identifying the current situation in knowledge-based systems and knowledge management. Specifically:

- the concepts and functions of knowledge management
- the major directions, elements, and stage of development in knowledge research and development
- the status of standards and procedures for the integration of multiple knowledge management systems

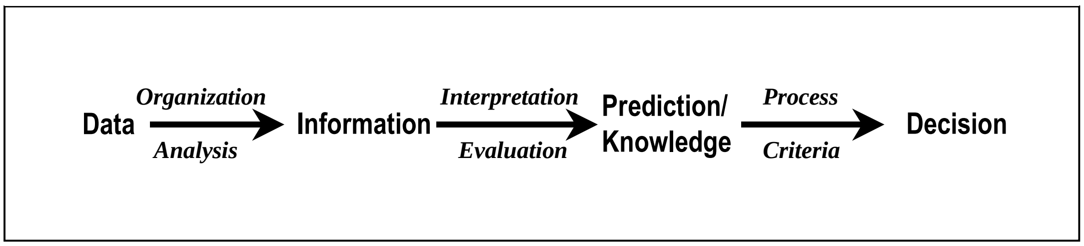
Finally, based on the literature and web review and on the review of knowledge-based systems being used in BC government resource inventories, recommendations were developed to assist with the future coordination and integration of knowledge-based systems into a corporate knowledge management system.

2. BACKGROUND

2.1. WHAT IS KNOWLEDGE?

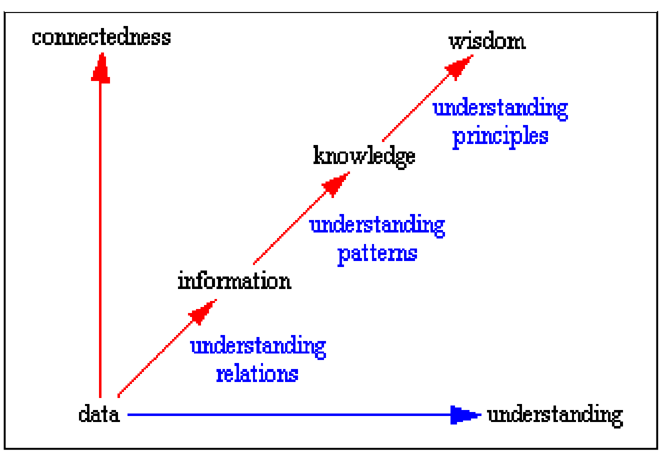
The definition of knowledge is widely if rather imprecisely understood. In the context of decision support, we have defined knowledge as a progression (Figure 1). In a progression we begin with data which is, on its own, of limited utility. By organizing or analyzing the data, we understand what the data means, and this becomes information. Understanding the meaning of the data (information) in the context of interactions, relations, or problems allows for the interpretation or evaluation of the data to yield knowledge or prediction. Finally, the application of a decision process and decision criteria leads to an action or a decision.

- **Figure 1: Knowledge Progression**

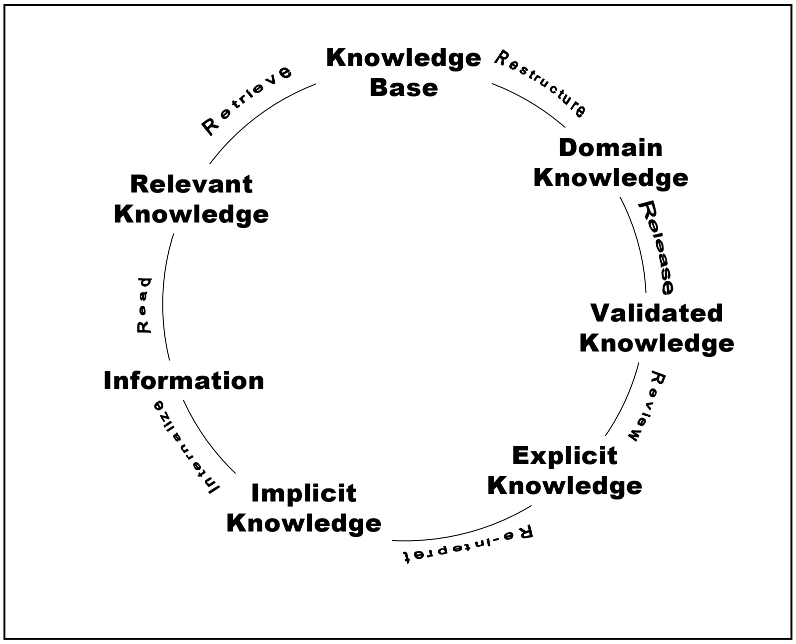


Gene Bellinger, in his Outsights "Mental Model Musing" web page, uses a slightly different definition. His concept is that as the degree of "connectedness" and understanding increase, we progress from data through information and knowledge to wisdom (Figure 2). While we may argue that understanding principles may encompass knowledge rather than wisdom, we will avoid the issue of what is truth altogether.

- **Figure 2 : Bellinger's Knowledge Model**



• **Figure 3: Knowledge Cycle**



Butcher and Rowley (1998) identified a counter-clockwise knowledge cycle that we have adapted to produce Figure 3. In their paper, they identified the seven R's of knowledge management:

- Retrieval – delivers relevant information or knowledge from the corporate knowledge base or from external sources.
- Reading – reading the knowledge retrieved provides information to the reader.
- Recognition (we call it internalizing) – internalizing the information places it in the context of a new problem, as well as the readers experience to create implicit (our term for what Butcher and Rowley call subjective) knowledge.
- Reinterpretation – reinterpretation in the new context and formalizing implicit knowledge converts implicit knowledge to explicit (our term for what Butcher and Rowley call public) knowledge.
- Reviewing – peer or operational review of the new explicit knowledge produces validated knowledge.
- Release – release of the validated knowledge adds to domain knowledge.
- Restructuring – restructuring the domain knowledge allows for its incorporation into the knowledge base.

Our use of the terms *implicit* and *explicit* knowledge generally corresponds to what other authors refer to as tacit and explicit knowledge and what still others have referred to as informal and formal knowledge.

This discussion is designed to convey the impression that knowledge is both more complex and useful than information or data and that it is strongly dependent on context. This complexity imposes a burden on information and knowledge management systems to provide the context that defines the information and knowledge. Thus, in the same sense that we require meta data to understand data, we will also require meta information and meta knowledge to understand and appropriately apply information and knowledge. The knowledge cycle also represents knowledge as an accretionary process with knowledge building on knowledge.

2.2. KNOWLEDGE FUNCTIONS

There are four functions associated with knowledge and knowledge management. These are knowledge acquisition, knowledge representation, knowledge management, and knowledge usage. These functions represent a logical sequence but are not necessarily formalized. For example, informal knowledge acquisition and usage may occur without formal knowledge structures or knowledge management procedures. The following discussion will introduce these four functions to establish context, but the remainder of the paper will concentrate on knowledge representation.

2.2.1. Knowledge Acquisition

Knowledge acquisition is the identification of relevant information sources and transformation of that information into knowledge. It involves at least the three activities described below.

2.2.1.1. Developing new knowledge (research)

Formal research programs are directed towards the development of new information and knowledge. These may be scientific research, market research, historical research, *et cetera*. They generally use well-defined and statistically based procedures and protocols. Much if not most research generates information, but when placed in context and used to create models (statistical or process), it generates knowledge. Things like experimental methods, comparisons with other research results, and the implications of the experimental results for current theory constitute a significant component of the knowledge produced.

2.2.1.2. Adding value to information to create knowledge

The evaluation and analysis of public and corporate data to identify patterns and relationships can create valuable knowledge. The highly promoted field of data warehousing and data mining are an increasingly significant component of knowledge creation. Data warehousing refers to the compilation of large amounts of public domain data, allies or competition data, and corporate operational and transactional data into a single database. Data mining refers to the analysis of this data to identify or confirm patterns and relationships using an array of tools ranging from spreadsheets and graphs to neural networks and multivariate analyses. The product of this process may be implicit or explicit knowledge.

2.2.2. Converting Implicit to Explicit

Human experience, without recourse to rigorous scientific procedures, often generates valuable knowledge. The term *tacit knowledge*, coined by Polanyi, 1977, refers to knowledge that is the result of the integration of personal experience, beliefs, perspectives, and values. While we call it implicit knowledge, it is the application of personal experience and beliefs with data and information from similar contexts for application to a new problem or issue at hand. This informal, tacit, or implicit knowledge and its conversion to explicit or documented knowledge is a major area of information research and is the principal target for many belief matrix and rule-based expert systems.

2.2.2.1. Knowledge Representation

Knowledge representation allows the storage of knowledge in structures that enable the fast and accurate access of knowledge as well as the easy understanding of the content and its structure (Brachman and Levesque 1985, Brachman *et al* 1992). Timothy C. Lethbridge presents an excellent overview of knowledge structures and retrievals in his PhD thesis (Lethbridge 1994). The conversion of implicit or informal knowledge to explicit or formal knowledge requires the creation of formal knowledge representations. These may be documents, diagrams, flow charts, databases, *et cetera*. The electronic storage and retrieval of knowledge requires the creation of formal knowledge structures such as ontologies, data models and schemas, semantic networks, *et cetera*. Formal knowledge representation is also a prerequisite for knowledge management. The knowledge representation will have a profound impact on both the efficiency of storage to and retrieval from the database. At present, knowledge representations for Predictive Ecosystem Mapping are of two kinds: belief matrixes and rule bases. Other representations such as ontologies, statistical and process models, and semantic networks will be discussed in later sections.

2.2.3. Knowledge Management

Knowledge management should allow for simple, yet powerful access to knowledge, and its update and usage (via reasoning). It should take into account differences among users and among requirements for different problem-solving tasks. Knowledge management, like data and information management consists of the following operations:

- Create – the entry of additional knowledge into the knowledge base. Creation in this sense does not refer to the development or acquisition of new knowledge. It refers rather to its entry into a knowledge base.
- Update – the modification of knowledge resident in the knowledge base.
- Retrieve – the retrieval of relevant knowledge from the knowledge base for application.
- Delete – the deletion or elimination of knowledge from the knowledge base.
- Archive[2] – the long-term storage of knowledge in a separate location from the active knowledge base. Archiving is done for security, for increased performance of the active knowledge base through the removal of no-longer-needed knowledge, or both.

The key to effective knowledge management is the representational model used to store and access knowledge in the knowledge base.

2.2.3.1. Delivery

The creation of a knowledge base provides little utility if the appropriate knowledge cannot be delivered efficiently and effectively for application to a problem. The user interface and information infrastructure will strongly influence delivery.

2.2.3.1.1. User Interface

A user interface, in a generic sense, is the means by which an individual gains access to data, information, or knowledge. It may be a card catalogue and the stacks in a library or a graphical user interface such as a web browser on a computer. Whatever the nature of the user interface, its role is to translate the underlying knowledge representations in a manner

[2] Archiving a knowledge base should not be confused with backing up a knowledge base. Archiving implies a software independent format with complete schemas and dictionaries to allow recovery of the knowledge independent of the original software used to create and manage the knowledge base.

intelligible to the user and to formulate the procedure required to retrieve the relevant knowledge.

2.2.3.1.2. Infrastructure

Infrastructure refers to the underlying foundation or framework on which knowledge delivery is based. This infrastructure includes hardware, software, organizational structures, and personnel. While not technically infrastructure, corporate culture and experience with the retrieval and use of knowledge in corporate business functions will strongly influence the success of knowledge management.

2.2.4. Usage

The use of knowledge is sometimes construed to require human cognition in the process, and therefore, computers cannot apply knowledge to a decision process. While this is an interesting philosophical point, we choose to accept the ability of both humans and systems to apply knowledge to a problem and to make decisions. Computer-automated mass transit (Sky Train) and mechanical processing are examples of computers applying knowledge (information in context) to make decisions.

2.2.4.1. Internalizing (understanding)

Knowledge practitioners, in order to use knowledge, must do the following:

- Define the context (the problem or situation) to which knowledge is to be applied.
- Acquire the relevant knowledge.
- Integrate the acquired knowledge with their experience and the context to determine the appropriate application of the acquired knowledge.

2.2.4.2. Application

Once context has been established and the appropriate application of knowledge determined, the application of knowledge can be automated. Systems designed to automate application of knowledge to a problem or situation have become known as knowledge-based systems.

The development of knowledge-based systems, while automating much of the application process, will not relieve the practitioner from establishing the context and determining the appropriateness of the knowledge base and knowledge engine to the problem or issue being addressed

3. .KNOWLEDGE SYSTEMS

The evolution of knowledge systems is paralleling the evolution of database management systems. Initial applications were tightly bounded and had narrowly defined goals and domains. As the complexity of problems increased, the bounds were loosened and the domains and goals expanded. This required a shift from concrete to abstract thinking and recognition of the need for meta data such as data dictionaries, data schemas, and data models. The increasing complexity of the problems also required the development of special languages to facilitate the retrieval of data from the computer and Structured Query Language (SQL) finally evolved as a *de facto* standard.

Current knowledge research and development are addressing four interdependent areas: Syntax, Epistemology, Semantics, and Ontology. These are explained, in simplified terms, below. Syntax is the system of rules and structures used to link language elements (words) in communication. Epistemology is the study of knowledge (in our context models of how things work). Semantics is the study of the origins and meanings of words. Ontology is the study of being and is frequently expressed in hierarchical classifications of concepts and relationships.

In artificial languages like computer programs, the language is highly bounded. Meanings are precisely defined, and the syntax provides the rigorous rules for conveying unambiguous instructions to the computer. In the scientific and technical disciplines, we attempt to model the processes that govern how things happen or work. Again, we use reasonably precisely defined terms and a relatively formal style of written communication based on the scientific method. We also use computer languages to model these processes, thus presenting an even more rigorous form of communication. In other words, science and technology are delving into the areas of epistemology using the well-defined syntax of computer languages.

When we move into the area of converting informal knowledge to formal knowledge, the problem becomes much more complicated. To begin with, we are dealing with natural languages and imprecisely defined concepts and words. Meaning is frequently context and syntax sensitive, and syntax is frequently irregular. The creation of knowledge dictionaries (semantics), knowledge schemas (structures), knowledge models (ontologies), and knowledge languages (syntax) requires working at a much higher level of abstraction and frequently deals with real objects only by way of example.

The progression *data* → *information* → *knowledge* therefore requires increasingly abstract tools to manage each level of progression.

3.1. EPISTEMOLOGICAL SYSTEMS (KNOWLEDGE-BASED SYSTEMS)

Epistemology is the branch of philosophy that studies the nature of knowledge, its presuppositions and foundations, and its extent and validity. We are primarily concerned with what is called *pragmatic epistemology*. According to pragmatic epistemology, knowledge consists of models that attempt to represent the environment in such a way as to simplify problem solving. No model can capture all relevant information, and even if it could, the model would be too complicated to use in any practical way. Therefore, we may require multiple models, although they may seem contradictory. The model most appropriate to a given situation depends on the problems that are to be solved. The basic criteria are that the model should produce correct (or approximate) predictions (which may be tested) or solutions to problems and that it be as simple as possible.

Perhaps the simplest definition of a knowledge-based system, is a system that applies knowledge to questions or problems to produce answers or solutions. A knowledge-based system requires at least two components: a knowledge base and an inference or knowledge engine that is used to apply the knowledge to the problem or question. Other components such as a user interface and reporting and tracing functions are also necessary and often are critical to the success or failure of the system. The following sections list some types of knowledge-based systems. These sections recognize as knowledge-based systems some approaches that are not traditionally viewed as knowledge-based systems. However, they do and should qualify as such based on the concepts developed above.

3.1.1. Taxonomic Models

Taxonomic models have been used extensively in agriculture and forestry for years. Soil, vegetation, and ecological inventories that are computer derived and based on interpretations are using taxonomic models. The knowledge base consists of observed or predicted responses to the taxonomic categories such as a site series or soil series of the taxonomic system. The knowledge engine is simply a look-up table used to replace the taxonomic category with the appropriate interpretation.

Taxonomic models are based on the assumption that either the diagnostic or the strongly associated attributes of the taxonomic categories are related to the interpretation being made. To the degree that this is true, the model works reasonably well. The knowledge base consists of the taxonomic class and a look-up table of interpretations associated with each class. The knowledge engine identifies the class and retrieves the appropriate interpretation from the look-up table.

We should make it clear that the taxonomy on which taxonomic models are based is more properly a narrowly defined ontology, but the use of its classes to make predictions is epistemological.

3.1.2. Empirical Models

Empirical or statistical models have also been used extensively for years. These models are based on statistical relationships between one or more “independent” variables and a dependent variable. In a multiple regression model, the knowledge base consists of the regression equation (both its form and coefficients). The knowledge engine retrieves values for the independent variables, applies the equation using these variables, and predicts the dependent variable. Other types of empirical models include non-linear regression, multiple discriminant analysis, de-trended correspondence analysis, *et cetera*. Examples include growth and yield equations, volume estimators, soil erosion predictors, *et cetera*.

Empirical models are not based on an understanding of how or why the independent variables affect the dependent variable; they are concerned only that they do. There is no underlying assumption of causality. As such, they are highly bounded.

3.1.3. Process Models

Unlike empirical models, process models presume to understand causality and to reflect this causality in the form of mathematical relationships. The knowledge base consists of the algorithms or computer source code and coefficients that define these mathematical relationships. The knowledge engine takes input data to define initial conditions and perturbations and then executes the algorithms to predict responses or changes in the system resulting from these perturbations.

To the extent that all of the processes are truly understood, the process model is not bounded and is in fact universally applicable in all situations where the processes operate. Pure process models are rare and most process models are in fact hybrids of empirical and process models. Indeed, both empirical and process models may make use of expert systems (see below) to provide estimates of input variables.

3.1.4. Expert Systems

One of the earliest recognized knowledge-based systems was the expert system. It's not that expert systems preceded taxonomic, empirical, and process models; it's just that the term *knowledge-based systems* was not elevated to pop-tech icon until after the advent of expert systems. Expert systems are an attempt to formalize heuristic (informal or rule of thumb) knowledge in a form that can be used by an inference engine to apply the knowledge to problems.

Most expert systems are rule based. That is, they use a series of if-then-else statements to process input data to a logical outcome. For example, if it is raining and I am going outside, I will get wet. The knowledge base is the rule set. The inference engine applies the rules to input data to infer a solution. It the system poses a question such as "Is this a cat?" and begins comparing the attributes of the thing being evaluated to the attributes of a cat it is said to be *backward chaining*. If the question posed is "What is this thing?" and the inference engine compares the attributes of the unknown to the rule base until arriving at an identification, the procedure is said to be *forward chaining*. Simple rule-based systems are binary; a condition is either satisfied or not, so partial or fuzzy membership is not accommodated.

Another approach to implementing an expert system is to use what is called a *belief matrix* as the knowledge base. The belief matrix records the belief in or the probability of an event or occurrence against a condition. In the case of identification, the belief class will occur under each of a specified set of conditions. The inference engine produces a weighted sum of beliefs for each condition, for each class and assigns the class with the highest weighted belief to the set of conditions. These approaches deal with a level of uncertainty, and a number of solutions with their attached belief values are possible.

A third approach to expert systems is a decision tree. Decision trees are similar to forward chaining, rule-based systems but uncertainty levels can be attached to each stage of the process. In this approach each possible solution is evaluated, and a final probability or certainty value is attached each solution.

A fourth approach, exemplified by Netweaver (Reynolds 1999), uses dependency networks (object-oriented, fuzzy logic networks), which offer several significant advantages over the more traditional rule-based representation. Compared to rule-based knowledge bases, dependency networks are more readily modularized, and therefore knowledge bases are easier to build, test, and maintain. This modularity allows designers to gradually evolve complex knowledge bases from simpler ones in small, simple steps. Modularity also allows interactive knowledge base debugging at any stage of knowledge base development, which expedites the development process. Finally, fuzzy logic provides a formal and complete calculus for knowledge representation that is less arbitrary than the confidence factor approach used in rule-based systems and much more parsimonious than bivalent rules. An interesting application of Netweaver links it to a geographic information system to provide automated inferencing of map objects.

Some expert systems approaches combine two or more of the above procedures into a single application or shell.

3.1.5. Artificial Neural Networks

Neural networks (Haykin, S. 1994) are a relatively recent development that attempts to emulate the learning process of real neural networks. A training data set with attributes assigned to known outcomes is used to train the system to process input data and return the predetermined solution. Once trained, the system can process attributes for unknowns to predict outcomes based on the training pattern developed with the training set. While some neural network approaches are original, most are based on traditional multivariate statistical procedures. The difference is that these systems frequently ignore the underlying property distributions on which multivariate approaches are based. They are, in fact, a variant of empirical models, and like other empirical approaches they are highly bounded (validated only to the conditions and data sets from which they were developed).

3.2. SEMANTIC SYSTEMS

Semantics is the study of meaning, as opposed to syntax, which is the study of the rules by which words and symbols are arranged to convey information.

3.2.1. Semantic Networks

Semantic networks attempt to represent meaning in formal computer constructs (Sowa 1991). They do this by defining nodes (concepts and instances) and formally defining relationships between nodes. Semantic networks implement at least three basic concepts: (1) deconstruction of information resources into a database of concepts and relationships among those concepts, (2) unique identity of information or data elements, and (3) explicit typing of relationships of meaning – for example, John Smith *is an instance of* man. Most semantic networks also implement some form of inheritance from abstract concepts, such as Dalmatian is a kind of dog. The relation implies inheritance of dog attributes by Dalmatian. Hypertext Markup Language (HTML) and Standard Generalized Markup Language (SGML) can be rudimentary semantic networks but the links are not necessarily semantic.

Semantic networks have been implemented in a variety of technologies including HTML, SGML, relational database management systems, and frame and object approaches (see Section 3.3.1).

3.2.2. Predicate Calculus

Predicate calculus, or the *Logic of Quantifiers*, is part of formal or symbolic logic. It systematically exhibits the logical relations between sentences purely based on how the predicates (noun expressions) are distributed through ranges of subjects by means of quantifiers such as all or some. Such predicates can include both quantities and relationships. For example the statement *All C are B and no B are A* requires that the statement *no C are A* be true. Therefore, the statement *no C are A* can be inferred from the first two statements and need not be explicitly stated. Predicate calculus and higher levels such as functional calculus have been used in attempts to develop a natural language knowledge base that will allow for what is called *automatic inferencing*.

Predicate calculus and predicate calculus-like languages have played an important role in the creation of knowledge systems such as CYC, Loom, and its successor PowerLoom. The CYC project (Lenat 1995) was initiated at the Microelectronics and Computer Technology Corporation (MCC) in Austin, Texas during the early 1980s. Unlike other large-scale knowledge applications, CYC is building a very large knowledge base. This knowledge base builds on logical assertions and presently contains approximately 400 000 significant assertions. These assertions include simple statements of fact, rules about what conclusions to draw if certain statements of fact are satisfied (true), and rules about how to reason with certain types of facts and rules. New conclusions are derived by the inference engine using deductive reasoning. The CYC project has developed a specialized language (CycL) that uses predicate calculus to create ontological frames as a way of overcoming limitations of predicate calculus to knowledge representation.

Another knowledge system that uses predicate calculus to derive frame-based knowledge structures is PowerLoom (Swartout 1995).

3.3. ONTOLOGICAL SYSTEMS

Ontology is the branch of metaphysics dealing with the nature of being. In knowledge management terms, ontologies are the formal specification of the entities, concepts, and relationships that are assumed to exist in some area of interest. In other words, a specification of a representational vocabulary for a shared domain of discourse – definitions of classes, relations, functions, and other objects – is called an ontology. Ontologies will form the basis for knowledge sharing between multiple knowledge bases in the same sense that data dictionaries form the basis for sharing between multiple databases.

3.3.1. Methods of Implementing Ontologies

Frame-based, and to a lesser extent object-based, approaches are being increasingly used in knowledge applications to create ontologies. Stanford University's Ontolingua (Gruber 1992), is perhaps the most well developed frame-based approach. Frame-based and object-based approaches to creation of ontologies have conceptual similarities. They can implement inheritance such that structured hierarchies of super classes, classes, and subclasses have each class inheriting attributes from all classes above it in the hierarchy. They can also implement multiple inheritance, whereby a class can be considered to inherit characteristics from more than one higher class. Both frames and classes are extensions of the data structure. The principal difference between frames and classes is that classes have, as an integral part of the structure, methods that perform some operation, whereas frames are manipulated by external functions. In many respects, there is a progression of integration between data and the operations performed on data. The progression goes from data structures to frames to classes.

The following material provides a sketch of the elements of frames and objects to demonstrate the conceptual similarity between the two approaches.

Frames

Frame – can be a Class Frame (entity), or an Individual Frame (instance).

Slots – are relationships (sets of characteristics or data elements) of Frames.

A frame may have many slots, but a slot can belong to only one Frame.

Slot Values – are assertions about the relationship, and a value may be another frame.

Facets – are domains that apply to slot values, and domains could be other frames.

e.g., Individual Frame *Fred* is an instance of Class Frame *Person* and has Slot *Favorite-Foods* with slot values *ice cream* and Frame *Potato-Chip.* (In this case a frame is being used as a slot value). Facet *VALUE-TYPE* having value *EDIBLE FOOD* restricts slot values of slot *Favorite-Foods* to slot values of Frame *EDIBLE FOOD*. (In this case a frame is being used as a facet).

Frame-based approaches still require the creation of knowledge manipulation procedures or languages.

Objects

Class – is an entity; Object – is an instance of entity.

Data Structures – are defined groups of data elements and can be mixed types and domains.

Assignments – assign attributes or variables to classes or objects.

Methods – are algorithms that direct how the object will respond to messages (calls) to an object.

Constructor – is a special method used to create objects (instances of classes); the constructor can include reference to "parent" classes to identify that new objects will be created with characteristics of the "parent" classes.

Messages – are external interfaces.

Unlike frames, classes can embed the methods to manipulate and communicate between knowledge structures in the class or object, but these methods must still be developed.

3.3.2. Relational Data Models

Relational data models can emulate many characteristics of both frame- and class-based ontologies. Through abstraction and the recognition of relation, operation, and domain entities, hierarchical knowledge structures such as ontologies can be emulated. The manipulation language (SQL) is already well developed but may not be as efficient as the procedures and languages being developed in frame- and object-based approaches.

We suspect that knowledge management approaches will ultimately be a hybrid of relational, frame-based, and object-based approaches. Some significant applications are already using this approach (Hendler *et al*, 1998). What is important to note is that all three approaches to defining ontologies use similar concepts and constructs. It is this similarity in concepts and constructs that offers hope that some unifying approach can be developed.

3.4. OTHER KNOWLEDGE STRUCTURES

There are, in addition to those described above, a number of widely used knowledge representations or structures. The oldest is probably the pictograph but today we have an array of representations from text (pamphlets to books), schematics, flow models, and computer data structures. These more traditional methods are being increasingly computerized so that we have computer programs designed to create text and image documents, schematics, and flow models. Many of the knowledge systems described above are using these capabilities to provide visual representations of knowledge structures, and interfaces to the knowledge systems.

4. COMMERCIAL KNOWLEDGE MANAGEMENT SOFTWARE

As discussed in Section 2.2.3, knowledge management consists of creating, retrieving, updating, deleting, and archiving knowledge. The management of the knowledge bases of knowledge-based systems, semantic networks and ontologies is only one component of knowledge management. In reality all or parts of the knowledge systems described above may be incorporated into a single knowledge management application. The following discussion outlines the scope and nature of knowledge management in order to place the management of knowledge-based systems in context.

4.1. WHAT IS KNOWLEDGE MANAGEMENT SOFTWARE

Just what is knowledge management software? A cynic might answer that knowledge management software is anything that can be packaged and sold under the heading of the vaguely defined term knowledge management. They would not be far wrong, and as new software ideas are generated, new applications will be sold under the heading of knowledge management.

4.2. TYPES OF KNOWLEDGE MANAGEMENT SOFTWARE

The following is a brief listing of the types of software applications that are being sold as knowledge management software. This list provides an operational synopsis of the current knowledge management applications and the formative stage of knowledge management.

Groupware. Groupware is technology designed to facilitate the work of groups. This technology may be used to communicate, cooperate, coordinate, solve problems, compete, or negotiate. While traditional technologies such as the telephone qualify as groupware, the term is ordinarily used to refer to a specific class of software relying on modern computer networks. Some applications provide specific functions such video conferencing, decision tracking, document and memo management, voting, and coordination. Underlying the organization and retrieval of documents are basic ontological approaches of organizing information and materials in a hierarchical structure that is designed to facilitate search and retrieval of relevant material.

Search Engines. Search engines, such as web browsers, are becoming an increasingly powerful knowledge acquisition tool. Search engines can be programmed to monitor the World Wide Web by reading web pages and creating word and concept indexes that are made available to clients for searches. Similar applications are available for indexing files resident on single computers, LANs, or WANs. These search engines are generally based on semantic networks and key-word searches and on semantic and syntactic rule-based inferencing.

Expert System Shells. Expert system shells are designed to allow the creation of a knowledge base (generally based on rules, belief matrixes, or dependency networks), without computer programming. The knowledge base can then be used to infer relationships, classes, or responses from input data.

Decision Support Systems. Decision support systems help business decision-makers solve unstructured problems. Although they appear to be used primarily by business managers now, everyone in the knowledge-based organization needs to make decisions based on an increasingly complex set of information variables. Decision Support Systems frequently integrate a number of knowledge tools including statistical analysis, geographic information systems, database management systems, optimization and scheduling tools, *et cetera*. At their current stage of development, decision support systems rely heavily on the array of epistemological systems.

Database technologies. Relational database and object-oriented database technologies are increasingly expected to support access to, and construction of, critical organizational knowledge resources, not just highly structured data. In the hands of imaginative designers, relational database technology can serve many of the functions of knowledge management. This includes the function of separating content and relationships in a networked environment that supports multiple users with concurrency control and rapid, continuous change.

Help-desk technology. Help-desk technology is used in many organizations as a way of responding to both internal and external customer knowledge requirements. The knowledge accumulated in using such systems typically has much broader application to rapid design and improvement of products and services. It's not just crisis intervention. Experiences with the routing and categorization functions of help-desk systems should provide a valuable base for other knowledge management technology. Help desk technology is exploiting areas of epistemological (expert systems), semantic networks, and ontological structures of knowledge organization.

Brainstorming applications. One class of software for brainstorming refers to tools for converting the tacit (informal) knowledge of individuals and groups into explicit knowledge and action that have value for the organization. Another class of brainstorming tools is designed to inspire creative thinking. The functions of both classes of products include categorization (ontology), organization for effectiveness, and identification of proximity of meaning (semantic networks).

Document management. Document management has many aspects. The contents of documents, together with the ways in which they are organized and accessed, form an explicit corporate intellectual asset. In addition to creating and maintaining manuals, brochures, and other documents, document management technologies use scanning and OCR tools to convert hard copy to digital copy, as well as word and concept indexing tools to capture knowledge.

Project management and Project tracking. These packages enable knowledge capture and distribution by documenting and communicating tasks, procedures, dependencies, and timing to project workers, and by providing a record of the project execution. Project tracking tools document variances from a plan. Using a project tracking tool to annotate the issues, problems, and solutions associated with each of the tasks and procedures followed in the project's execution can provide valuable knowledge for subsequent implementations. Project management and tracking packages also support communication and tracking for standard operating procedures or analytical services.

Visual modeling. These packages provide tools to graphically create complex decision systems or simulation models. For simulations, these packages use a set of objects, such as flows, rates, and stores. They function like graphical spreadsheets. Instead of referencing cells and populating cells with values, functions, or references, a visual modeling package allows users to sketch processes as stores, sketch flows between stores, and sketch the controls that influence rates of flow, inputs or outputs. Most visual modeling packages allow visual equation definition. Users draw a graph of the relationship they wish to use to define a function and the system generates the appropriate equation for use in the function. Visual modeling packages can effectively model a variety of simulations including feedback loops.

Visual modeling tools for decision trees graphically model the elements influencing the decision process, decision points, probabilities and outcomes. They then solve the problem. Some of the more sophisticated systems allow users to graphically create linear and non-linear optimization models.

5. THE CURRENT SITUATION

5.1. APPROACHES TO KNOWLEDGE MANAGEMENT

The following discussion, taken from Barclay and Murray (1997), editors of the online magazine *Knowledge at Work*, assesses three approaches to knowledge management. We agree with their assessment and therefore quote them directly.

> **Mechanistic approaches to knowledge management**
>
> Mechanistic approaches to knowledge management are characterized by the application of technology and resources to do more of the same better.
>
> The main assumptions of the mechanistic approach include:
>
> Better accessibility to information is a key, including enhanced methods of access and reuse of documents (hypertext linking, databases, full-text search, etc.). Networking technology in general (especially intranets), and groupware in particular, will be important solutions. In general, technology and sheer volume of information will make it work.
>
> Assessment: Such approaches are relatively easy to implement for corporate "political" reasons, because the technologies and techniques — although sometimes advanced in particular areas — are familiar and easily understood. There is a modicum of good sense here, because enhanced access to corporate intellectual assets is vital. However, it's simply not clear if access itself will have a substantial impact on business performance, especially as mountains of new information are placed on line. Unless the knowledge management approach incorporates methods of leveraging cumulative experience, the net result may not be positive, and the impact of implementation may be no more measurable than in traditional paper models.
>
> **Cultural / behavioristic approaches to knowledge management**
>
> Cultural / behavioristic approaches, with substantial roots in process re-engineering and change management, tend to view the "knowledge problem" as a management issue. Technology — though ultimately essential for managing explicit knowledge resources — is not the solution. These approaches tend to focus more on innovation and creativity (the "learning organization") than on leveraging existing explicit resources or making working knowledge explicit.
>
> Assumptions of cultural / behavioristic approaches often include:
>
> > Organizational behaviors and culture need to be changed dramatically. In our information-intensive environments, organizations become dysfunctional relative to business objectives.
> >
> > Organizational behaviors and culture can be changed, but traditional technology and methods of attempting to solve the "knowledge problem" have reached their limits of

effectiveness. A "holistic" view is required. Theories of behavior of large-scale systems are often invoked.
It's the processes that matter, not the technology.
Nothing happens or changes unless a manager makes it happen.

Assessment: The cultural factors affecting organizational change have almost certainly been undervalued, and cultural/behavioristic implementations have shown some benefits. But the cause-effect relationship between cultural strategy and business benefits is not clear, because the "Hawthorne Effect" may come into play, and because we still can't make dependable predictions about systems as complex as knowledge-based business organizations. Positive results achieved by cultural/behavioristic strategies may not be sustainable, measurable, cumulative, or replicable … and employees thoroughly "Dilbertized" by yet another management strategy may roll their eyes. Time will tell.

Systematic approaches to knowledge management

Systematic approaches to knowledge management retain the traditional faith in rational analysis of the knowledge problem: the problem can be solved, but new thinking of many kinds is required.

Some basic assumptions:

Sustainable results matter more than processes or technology … or your definition of "knowledge."
A resource cannot be managed unless it is modeled, and many aspects of the organization's knowledge can be modeled as an explicit resource.
Solutions can be found in a variety of disciplines and technologies, and traditional methods of analysis can be used to re-examine the nature of knowledge work and to solve the knowledge problem.
Cultural issues are important, but they too must be evaluated systematically. Employees may or may not have to be "changed," but policies and work practices must certainly be changed, and technology can be applied successfully to business knowledge problems themselves.
Knowledge management has an important management component, but it is not an activity or discipline that belongs exclusively to managers.

Assessment: Unrepentant rationalists in the business world are taking a systematic approach to solving the "knowledge problem." You'll also find evidence of such approaches — as well as a less formal use of the term systematic knowledge management —Karl Wiig's Knowledge Research Institute Web site and Gene Bellinger's Systems Thinking Web pages. Systematic approaches show the most promise for positive cumulative impact, measurability, and sustainability.

5.2. THE CURRENT STATE OF KNOWLEDGE MANAGEMENT

The vagueness of definition and the array of diverse software applications marketed under the rubric of knowledge management are not surprising, since knowledge management is at an early evolutionary stage. There is a growing recognition of the need for and advantages of knowledge sharing and re-use between systems (Gennari 199?, Genesereth 1991, Gruber 1993, Grosso 1998, Skuce 1997). A number of ontological systems are competing for *de facto* standard status (Chaudhri *et al* 1997). HTML, SGML, and HyTime are competing for standard status in text markup. Common Object Request Brokering Agent – CORBA (Mowbray 1997) – is established as one standard for object sharing. However, the CORBA standard is primarily syntactic rather than semantic and there is no assurance that an object called will function as expected or that it will carry the expected meaning. In addition, there is research being done on knowledge retrieval languages (Finin *et al* 1992, Finin et al 1995).

5.3. STANDARDIZATION PRIORITIES

The emergence of knowledge management as an integrated and coherent set of tools and concepts is going to require the development of at least the following knowledge specific components:

- consistent and widely accepted knowledge models (ontologies)
- consistent and widely accepted knowledge structures (schemas)
- consistent and widely accepted knowledge manipulation language, which will in turn require:
  - a consistent and widely accepted knowledge dictionary
  - a consistent and widely accepted knowledge syntax
  - consistent and widely accepted inference mechanisms

6. CONCLUSIONS

The arena of knowledge management and knowledge-based systems is very volatile. The growing array of knowledge-based systems, approaches to knowledge processing, and approaches to knowledge representation are presenting the same problem that early database management presented. We are developing potentially incompatible knowledge bases and knowledge-based systems that will present significant difficulties when attempts are made to integrate them into a corporate structure.

It would be premature to attempt the unilateral establishment of knowledge standards in an area evolving as rapidly as knowledge management and knowledge structures. It is also clear that the current hype about knowledge management will dissipate long before its potential is fully realized. This has been true for database management, remote sensing, geographic information systems, and expert systems. But is also clear that by the time the hype dies down, knowledge management and knowledge-based systems will be an established and growing component of almost all product and service organizations.

6.1. KNOWLEDGE BASE INTEGRATION

It would be relatively easy to develop a simple knowledge structure that could be used to document and allow the exchange of the knowledge bases being used in predictive ecosystem mapping. However, this knowledge structure would be restricted to belief matrixes and rule sets. They would not accommodate the wide array of knowledge structures that have potential application to predictive ecosystem mapping.

It is feasible to develop a knowledge structure that could be used to document and allow exchange of the all knowledge structures reviewed in this report. To be used as a knowledge-base repository, this structure would require a set of utilities to import and export the various knowledge structures extant and evolving. Such a system, while having the advantage of storing the contents of multiple knowledge bases, would not provide an integrated knowledge base unless we also have the knowledge-specific components described in Section 5.3.

Unfortunately, knowledge management is a very volatile field and the PEM knowledge structures used in BC represent a small component of possible approaches to PEM. The establishment of knowledge-structure and knowledge-exchange standards at this time would almost certainly prove counter productive and restrictive. It would also, almost certainly, be obsolete before completion.

We are not suggesting that there is nothing productive to do. We should think **seriously** about the needs of knowledge exchange, work to coordinate our efforts, and most importantly document, document, and document. In particular, we could document, against a generic knowledge structure, the ontology of ecosystem mapping including the inputs to predictive ecosystem mapping (e.g., forest cover, vegetation, terrain, and soil).

It seems logical, therefore, to accept the inevitable impact of knowledge-based systems and knowledge management on Terrestrial Ecosystem Mapping and Predictive Ecosystem Mapping. It also seems logical to attempt to minimize the difficulties associated with integrating disparate knowledge-based systems into a corporate knowledge base as standards evolve. The key to this integration will be the effective and complete documentation of the knowledge-based systems used in TEM and PEM.

6.2. DOCUMENTATION

There are three critical elements required to document a knowledge-based application:

- Knowledge representation – the concepts and structures used to store the knowledge encompassed in the knowledge base.
- Knowledge processing – the algorithms and procedures used to apply the knowledge base to a situation.
- Rationalization or theory – the underlying theories or reasons on which the knowledge base values and processing algorithms or procedures are based.

It is possible to provide all three elements of documentation as integral components of the knowledge system itself, but it should also be possible to generate them as independent documents. Current approaches to documenting relational databases provide a good model and provide much of the required information. The documentation should, as much as possible, be independent of the software package, programming language, or the physical implementation used.

7. RECOMMENDATIONS

The following recommendations are based on an understanding of the history and problems associated with database management. It would be fair to say that the problem of integrating knowledge bases will be an order of magnitude greater than that of integrating databases. It is instructive to note that most organizations have yet to successfully integrate their disparate databases.

7.1. DEFINE LIMITED SCOPE FOR FUTURE WORK

The issue of corporate knowledge management, while comparable to corporate data and information management, is significantly more complex and larger in scope. The Resources Inventory Committee (RIC) should carefully consider the scope of knowledge management and determine what if any elements fit within their mandate for standards. The management of inventory-related knowledge-based systems and their supporting databases may be appropriate. Specifically this should include:

- Taxonomic models
- Empirical models
- Process models
- Expert systems
- Ontological classifications

7.2. CONDUCT INVENTORY OF KNOWLEDGE-BASED SYSTEMS

If standards pertaining to knowledge-based systems and knowledge management are within the mandate for standards, they can be justified on the need for knowledge base and knowledge-based systems integration. A pre-requisite for the development of standards to support integration is an inventory of the knowledge-based systems currently used for inventory-related tasks. The inventory should include:

- the business area and processes supported by each system
- the knowledge products produced and their application
- the type of system, knowledge structures, and inferencing procedures used
- the input requirements and formats
- the level and completeness of supporting data and documentation.

7.3. ESTABLISH DOCUMENTATION STANDARDS

Establish a set of documentation and meta-data standards for current and proposed knowledge-based applications. The nature of the documentation will vary depending on the type of knowledge-based system being documented but should include:

- A description of the knowledge structures used. The documentation will vary depending on the knowledge structures used but should include a description of:
  1. Frames (including slots, slot values, etc.) for frame based systems
  2. Classes (including methods, data structures, etc.) and Objects for object based systems
  3. Entities and Relations (including membership rules, domains, etc) for relational data based systems

4. Column and row definitions together with the method and domain definitions of cells for belief matrix based systems

   For large knowledge bases, this could be onerous, and an alternative would be examples and automated procedures to produce the descriptions.

- A description of the inferencing processes used including rule bases, decision trees, simulation models, knowledge retrieval algorithms, or processing functions.

7.4. DOCUMENT THE ECOSYSTEM ONTOLOGY

It is important that the concepts, processes, and criteria underlying the ecosystem classification be formally and unambiguously documented in computer retrievable format as a formal ontology. The ontology would identify the dominant processes acting at each level of the classification and the balance of processes and the mechanisms by which the balance is presumed to produce the classes identified at each level. The ontology would be structured around the TEM classification system with the processes, balances, and mechanisms documented as relationships between classes at the same level, between levels, and between classes at different levels. The integration of the ontology with a database of class attributes would provide an effective standard for communication, correlation, and quality assurance and quality control.

While the information necessary to construct the ontology exists, it is in the form of internal documents, conference presentations, manuals, and scientific papers. This material should be compiled as a formal ontology in a generic knowledge structure that can be accessed by workers in the predictive ecosystem mapping field. The ontology could be used to ensure that workers are using the correct ontology, that they are applying it appropriately, and that class attributes are consistent with the ontology. The ontology, not the generic knowledge structure should be established as a TEM and PEM standard.

7.5. PROVIDE COORDINATION

Conduct annual meetings of public and private knowledge-based system developers to discuss issues of knowledge representation, knowledge retrieval and processing, and knowledge exchange. The initial meeting may include formal presentations on the subjects of knowledge representation, knowledge retrieval, knowledge processing, and knowledge exchange by knowledge management specialists.

When the magnitude of knowledge-based systems work warrants, create a public and private sector working group on knowledge standards and knowledge exchange.

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