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The Cognitive Basis of Knowledge Engineering

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Abstract. The goal of knowledge engineering is to create an artificial system which reflects knowledge-like qualities. Current tools, techniques and procedures in knowledge engineering concentrate on the elicitation and representation of knowledge structures. This concentration of effort reflects the current emphasis on the epistemological and computational/representational characteristics of knowledge engineering. A different, yet complementary perspective is offered in this paper. Knowledge engineering is defined as a human activity system, characterized as a cognitive environment or network which deals with complex epistemological domains. Rather than viewing knowledge engineering as entirely concerned with knowledge content, those processes which produce the knowledge in the knowledge engineering environment are viewed as the focus of attention. Memory, judgment and choice, text comprehension, and social cognition and communication represent a selection of cognitive science domains which offer research findings of importance for knowledge engineering. Based on these research findings, the groundwork is laid for the development of cognition-support tools for knowledge engineering.

1. Introduction and Purpose

The domain of knowledge engineering has focused on the acquisition and modelling of knowledge. This is not a surprising statement but it raises an important issue which this paper addresses. The terms 'acquisition' and 'modelling' would first suggest an emphasis on the processes and procedures related to knowledge engineering but a closer look suggests that the focus is rather on the outcome of these processes. The 'knowledge' focus dictates that whatever processes are developed, or adapted, they must result in structures which somehow 'capture' or 'represent' identified forms of 'knowledge'. The tools, techniques and procedures developed to acquire knowledge are classified as either 'domain-specific' or as 'generic'. The term 'domain- specific' denotes a tool, technique or procedure which has developed out of knowledge engineering within a defined domain (eg. Opal: see Musen, 1989). The content, or the specific knowledge structures of the domain, guide and determine the tool, technique or procedure to be used. Generic tools (eg. KSSO: Gaines, 1988) are those which are considered to be useful and appropriate in a wide variety of domains. In this case, the tool guides the type of content which will be specified from the domain. *The results of these tools are knowledge-specific structures.*

This paper presents arguments and research support for the development of a different category or class of knowledge engineering tool: cognition-based tools. This type of tool is characterized by a de-emphasis of the 'knowledge' itself with a greater emphasis on the cognitive activities abundant in knowledge engineering activity which produce knowledge structures. These cognitive processes inherent in the knowledge engineering process establish the cognitive basis for knowledge engineering. The selection is based on sites of cognitive activity not solely on domain tasks or knowledge centred generic processes. Rather than emphasizing processes which identify domain tasks and knowledge structures, this approach emphasizes the support for the cognitive process activity in knowledge engineering.

Knowledge engineering is viewed as a body of activity which is characterized by intense cognitive activity as well as a strong emphasis on knowledge structures. Section 2 presents the main premises for viewing knowledge engineering from a cognitive processing perspective rather than from a knowledge perspective. Knowledge engineering is defined as a human activity system consisting of different sites and levels of cognitive activity. The cognitive processes occurring at each site and between sites constitutes part of the cognitive environment. The focus of this paper is on the cognitive processes of the knowledge engineer. Section 3 presents research on the processes involved in understanding new, complex domains (a usual experience for knowledge engineers). Sections 4 through 7 present cognitive research relevant for knowledge engineering: memory, text comprehension, judgment and choice, and social cognition.

2. Knowledge Engineering Viewed as a Collection of Cognitive Processes

2.1 The Current Focus in Knowledge Engineering

The domain of knowledge engineering reflects a strong emphasis on the acquisition and modelling of knowledge structures and the processes to manipulate and transform them. These aspects may be categorized as the epistemological nature of the domain. Epistemological and accompanying ontological discussions are concerned with the concepts selected to express the various structures for acquisition and modelling. This emphasis reflects the importance of concepts like the 'knowledge level' (Simon, 1988) and the research on 'expertise' and expert knowledge (eg. Johnson, 1986). Results of these studies centre predominantly on expert-novice differences in conceptualizing the domain problem, in the knowledge structures used in finding a solution, and, to a lesser extent, in the different methods used to solve the problems.

Discussions concerning the nature of knowledge also characterize the domain of knowledge engineering. These discussions include the role of different types or forms of knowledge in meeting tasks demands. The KADS (Wielinga, et al, 1989) methodology in knowledge acquisition is based on a strong epistemological foundation. A parallel approach to the development of re-useable problem solving structures and processes is represented by role-limiting methods (see Marcus, 1988) and generic tasks (Chandrasecaran, 1988). This research points to the need for identifying usable knowledge structures and the processes by which these structures are manipulated.

A related issue is that of knowledge representation. Representation frameworks abound and they will not be discussed here (see Brachman and Leveque, 1985). The discussion of forms and structures of knowledge logically lead to the issues of how to represent that knowledge in a form useful for modelling. Selected epistemological constructs act as the basis for knowledge structures and are used to impart meaning. Formal languages and representational frameworks determine what is computationally tractable. Epistemic

concepts are used to develop formal structures and these structures are used to order and arrange the knowledge of a given domain.

2.2 The Cognitive Aspect of Knowledge Engineering

Knowledge engineering activity has been largely focused on the epistemological and representational aspects of knowledge. A different, yet complementary view would identify knowledge engineering as the interaction of cogniting agents with the emphasis on the cognitive processes used in knowledge engineering. The knowledge-intensive approach in current knowledge engineering forces us to view the outcome or the product of our efforts as most important. The 'knowledge' is 'acquired', 'transferred', 'captured' and 'modelled'. This emphasis directs our attention away from the processes that 'produce', 'organize', and 'represent' the knowledge: away from notions of learning, comprehending, and communicating. Perhaps these processes are taken for granted; perhaps they are considered invariable. This emphasis is clearly displayed in our tools, techniques and procedures in that they focus on structures of knowledge and the processes used to manipulate them. Few of our tools address the complexity of the cognitive processes used to develop the knowledge structures although many of our knowledge acquisition tools support them.

Perhaps another reason for our present emphasis is the inconclusive nature of cognitive processes. Perhaps we understand these processes far too little or view them as problems and sources of noise to use them effectively in our work in knowledge engineering. We try to avoid the biasing nature of the knowledge engineer's presence in the development of knowledge-based systems. Our approach is to develop methods to 'capture' the expert's knowledge automatically and directly, thus eliminating the influence of the knowledge engineer. This view might alter if cognitive processes were viewed as a necessary component to knowledge engineering in that we cannot fully understand knowledge and its re-creation if we fail to understand those cognitive processes involved.

Wetter and Woodward (1990) have identified the importance of incorporating an understanding of cognitive processes in the development of a theory of knowledge acquisition. In order to develop a method of knowledge acquisition in a principled manner, the epistemic concepts must be clearly defined, the epistemic concepts must have a basis in psychological occurrence, and the representational formalism must reflect the intended epistemic and psychological meaning.

Rather than viewing the domain of knowledge acquisition from the epistemological or representation perspective, this paper addresses the domain from the cognitive perspective. This perspective is viewed as complementary to the epistemological and representational ones in that it helps to complete the picture. The cognitive perspective is characterized by an emphasis on cognitive processes, their identification and support, rather than on the identification and production of knowledge structures. The question here is not 'Where's the knowledge ?' but 'What cognitive processes produce the knowledge?'

2.3 Knowledge Engineering as a Set of Cognitive Processes

This section sets out the premises for viewing knowledge engineering as a set of cognitive processes rather than as a set of activities which acquires and models knowledge in one form or another.

First, knowledge engineering represents an ordered collection of cognitive activities. From an information processing point of view, cognitive activities are explained as processes of a "physical symbol system (eg. human brain) consisting of a representation system and the

processes to manipulate it" (Aitkenhead and Slack,1985). This is a broad definition which includes human cognition as well as physical symbol systems which display cognition-like processes. Cognitive activities may be ordered and contained within one physical symbol system or shared between interacting physical symbol systems.

Second, the purpose of knowledge engineering is to use cognitive processes to produce a model which demonstrates cognitive properties. This premise suggests a comparison point between the goals of cognitive psychology and those of artificial intelligence in that the outcomes of each are considered models. Aitkenhead and Slack (1985) point out that in those disciplines concerned with cognitive processing and modelling the formulation of information processing models are evaluated against a body of experimental data. In artificial intelligence, the goal is to build computer-based models of performance which are evaluated against criteria such as computational efficiency and logical coherence. The focus of the former is on the final model and its ability to account for evidence of cognitive structures and processes. The focus of the latter is on the computational attributes and usefulness of the final model. Viewing knowledge engineering as a set of cognitive processes means that we emphasize the information processing activities which lead to a final model rather than the characteristics and content of the final model.

Third, knowledge engineering is done in a cognitive environment. The environment defines a set of situations in which information is generated and produced, provided, manipulated, organized, re-organized and re-represented. The environment also defines those processes and structures which are used to generate, manipulate, comprehend, and organize the information. These processes are concerned with meaning, not just information. In this sense, the environment we are defining here might be called a 'knowledge' environment but that would suggest we are interested more in the outcome of the meaning or in asking 'what is the meaning' of a certain piece of information. However, we are more interested in asking 'how is the meaning' of a certain piece of information determined. Consequently, our interest is on the cognitive processes of developing meaning. In this environment, humans are involved and they supply many of he cognitive processes.

Fourth, the cognitive environment is characterized by sites and levels of cognitive activity. The environmental structure determines the locations of activity and the types of cognitive activity which occur at those locations. Sites refer to those clearly distinguishable points of cognitive activity (eg. the knowledge engineer, expert). Level refers to various combination of sites which are in interaction. Interaction of cognitive processing sites entails another level of cognitive activity which is distinguishable from cognitive activity occurring at a single site. For example, single site activity (eg. the expert) may reflect processes leading to making a choice about a course of action. Interaction of sites requires the use of social cognition processes. Presently, our field is much more fascinated with the cognitive processes of the expert but less so with those of the knowledge engineer and the user. In fact, we try to eliminate the cognitive effect of the former and ignore that of the latter. Why do we wish to develop our understanding of cognitive processes at one significant site in knowledge engineering and not others ? The expert's cognitive processes as well as those of the knowledge engineer and the user are open for our observation and study because they a part of the knowledge engineering environment. Addressing cognitive processes separately and in interaction may bring us better understanding of the knowledge engineering process.

Fifth, an understanding of the cognitive environment acts as a basis for developing tools, techniques, and procedures to support and/or replace these processes. With our emphasis on the cognitive aspects of knowledge engineering, the focus of potential support processes is based on our understanding and careful elucidation of those cognitive processes which are characteristic of sites and levels of cognitive activity. Rather than emphasize knowledge

support we are suggesting a complementary view of cognition support as a basis for tool, technique, and procedure development. For example, in addition to asking questions based on the domain content and problem-solving heuristics, it is useful to ask questions which are formed to reflect different cognitive processes (eg. LaFrance, 1986).

3. Cognitive Characteristics of the Domain of Knowledge Engineering

3.1 Understanding Complex Domains

The role of the knowledge engineer is cognitively demanding in that the knowledge engineer is expected to enter into the epistemological structure of a domain far enough to build a model of that domain. Even if the domain is restricted in scope, the knowledge engineer must become familiar with the problem-solving structures in the domain and the underlying assumptions of the domain of interest. These demands are similar to expert development within that domain in that the knowledge engineer, as a novice, must quickly become familiar with the necessary epistemological concepts and problem-solving processes in order to adequately model the domain or part thereof. When a knowledge engineer enters a new, complex, epistemological domain, he/she uses a variety of cognitive processes to first understand and comprehend the basic structures and assumptions of the domain and second, to model this understanding. It is these cognitive processes which require identification and description so that tools, techniques, and procedures may be developed as aids and supports to the knowledge engineer alone or in interaction with the expert.

The development of problem-solving skill in medicine acts as a case in point. Research on how medical students and interns come to develop expertise in a complex epistemological domain parallels the cognitive demands placed on the knowledge engineer when he/she enters a new domain. Evans (1989) stresses that addressing the complex domain of medical problem-solving reflects four critical issues:

> "1)the relation between domain knowledge and problem-solving behaviour; 2) the sources of bias and misconception in problem representation and decision-making; 3) the role of discourse in structuring the acquisition of data..., and 4) the identification of formal methods for the evaluation of performance" (p. 2).

These same issues are of importance to the knowledge engineer and to knowledge engineering activity. The point here is that the knowledge engineer is required to learn something about the domain in order to make knowledge engineering decisions. The cognitive demands placed on a knowledge engineer when he/she enters a new domain are similar to novices in that domain who are in the process of developing a greater understanding of the domain. The rest of this section presents research support for a number of cognitive processes involved when an individual is developing understanding in a complex domain.

3.2 Cognitive Processes in Understanding

The biomedical domain is characterized as epistemologically rich. Many of the concepts and families of concepts are highly interdependent, forming extremely complex epistemological networks. Meaning and understanding of the concepts alone as well as the interactions of these concepts are necessary for understanding the domain. Understanding is often hampered not only by the complexity but by the ill-structured nature of the domain. A number of researchers have reported the difficulties of understanding complex systems

(Flood, 1987) as well as the requirements and methods for overcoming these difficulties (Cairns and Woodward, 1988). The novice and the knowledge engineer are similar when they embark on conceptual analyses of clusters of complex concepts.

Patel et al (1989) identified a number of cognitive processes used in developing a functional relationship between biomedical knowledge and clinical reasoning. The following cognitive processes were viewed as necessary for developing an understanding of how to incorporate models of biomedical knowledge in diagnosing clinical cases. These processes included comprehension of text-based propositions, construction of consistent and coherent explanations, and selection of relevant and irrelevant facts based on clear discrimination principles. These findings are based on novice-expert interactions and they represent points of distinction between novice and experts in the domain. Knowledge engineers resemble novices (or even sub-novices) when they first enter a new domain. The cognitive processes used by novices, which distinguish them from experts, are identified as correlates of poor understanding, diagnostic performance, and explanatory performance.

Another set of studies (Feltovich et al, 1989, 1984; Spiro et al, 1988, 1990) addresses the nature of conceptual understanding in biomedicine. More specifically, the studies address how deep models of complex ideas develop and how problems may arise with these models, during their development, which lead to misconceptions. The results have shown developmental patterns for a variety of biomedical misunderstandings. The results support three main reasons for misunderstandings: multiplicity, interdependency and oversimplification. The first refers to the fact that many influences contributed to the acquisition and maintenance of misconceptions such as learner style and ability, the methods of education, and practices of biomedical science research. The second characterizes misconceptions as reciprocating networks based on basic component ideas which are faulty. These networks tend to support each other or positively reinforce each other so that misconceptions are promulgated throughout the network. The final pattern suggests that due to human information processing capacity, the complexity of the concepts is reduced by selecting, collapsing or relating concepts in a way which changes the meaning.

3.3 Cognitive Demands on the Novice

Complex concepts make unusual cognitive demands on the novice. Feltovich et al (1989) describe four main demands on:

1. working memory because of the large number of nested or looped steps or goals, or because of the large number of variables to be considered, processed, and/or reconciled;
2. formal representation in the sense that the degree of abstraction necessary for understanding is often onerous (eg. representing the concept of rate or acceleration);
3. intuition or prior knowledge in the sense that new concepts can conflict with prior meanings and/or relationships among concepts; and
4. notions of regularity because many concepts can be ill-structured and highly variable in how they are used or they may be very strongly dependent on other concepts for their meaning.

These same demands are placed on the knowledge engineer. These cognitive demands affect knowledge engineering activity by leading to misconceptions which may be perpetuated into the final system if not 'caught' by the expert (assuming there exist specific procedures for the expert to use to 'catch' the misconception). Also, when complex conceptual domains are addressed, complexity reduction occurs. Many researchers have studied the processes whereby humans use particular procedures to reduce the complexity

of conceptual information. (Kahneman and Tversky, 1973; Kahneman et al, 1982; Coulson et al, 1986; Spiro, 1980).

Feltovich et al (1989) distinguishes conceptual bias from those biases in judgment and decision-making (Kahneman et al, 1982) in that the family of 'reductive biases' are used solely to reduce complexity rather than reflect judgment processes. Six reductive biases were identified. 'Static' bias occurs when a dynamic system is viewed as a static model. 'Step-wise' bias describes the situation where a continuous process is broken down into discrete, identifiable steps resulting in a loss of meaning. 'External agent' bias is the attribution of essential intrinsic characteristics of entities or processes to external influences. 'Prior analogy' bias occurs when new concepts are given meaning based on already held concepts or simple models within the domain or from other domains. 'Common connotation' bias occurs when technical terms are reduced in meaning based on the day-to-day use of the term or concept. Finally, 'restriction of scope' bias refers to the belief that general principles are taken to apply only under certain circumstances based on a repeated co-incident relationship.

3.4 Methods of Information Presentation

One important issue addressed in the research in the biomedical domain is the need to select the 'right' concepts for presentation (Feltovich et al, 1989). Due to the complex, ill-structured nature of certain facts of a domain, the tendency is to present information initially in a simple overview format and then to incrementally increase the complexity so that models are built to a point of greater sophistication (Glaser, 1984). The reason to select the right concepts is due to a perceived failure of this incremental approach. These researchers found that students used the simplified models to 'filter-out' or arrange later material so that developing an understanding of the complexity did not occur. Also, they found that the initial simplification promoted further simplification of ideas. The tendency was to under-dimensionalize. The recommendation is to select key concepts, to ensure that they are understood, and then to build around the key concepts. Criteria for selection of these key concepts are the perceived importance of the concept by the community, the degree of centrality of the concept in the literature and for clinical cases, a high degree of difficulty in understanding the concept, and the concept has cross-context application.

A second issue emerging from the biomedical research suggests the use of abnormality models of information processing. This type of model is extremely useful in identifying, describing and correcting processes which result in some form of misunderstanding. These models frame a conceptual misunderstanding in terms of the processes used to develop it. These types of models appear to have a real application in knowledge engineering. Often the knowledge engineer needs to use the expert as the best guide to conceptual verification; however, only content is addressed. Procedural models of common processing biases or distortions (abnormalities) might be used by the knowledge engineer in verification of knowledge-based systems.

3.5 Summary

The biomedical research demonstrates the value of studying the cognitive processes of learning in the context in which they occur. In most cases the research was carried out in the classroom and teaching hospitals associated with medical schools. If we are to learn more about the cognitive processes involved in knowledge engineering, the actual context becomes the laboratory.

Also, the research presented from the biomedical field provides an example of the importance of understanding the cognitive processes involved when an individual attempts

to comprehend a complex epistemological domain. Knowledge engineers are constantly confronted with this task and the cognitive demands placed on them are onerous. This research has indicated that identifiable cognitive processes are involved in the understanding of complexity and has provided some direction for the development of cognition support tools, techniques and procedures for knowledge engineering.

The following sections of the paper identify and describe other sets of cognitive processes apparent in knowledge engineering activity.

4. Memory

4.1 Types of 'Memory'

Commonly agreed upon mechanisms of memory (Potter, 1990) support memory as a three phase phenomenon. Processes are postulated for information registration or encoding, for retrieval or remembering, and for forgetting. Temporal architectures have also been postulated (Crowder, 1982). Gorfein and Hoffman (1987), Klatzky (1980), and Crowder (1976) provide good evaluations of the memory research. For knowledge engineering, specific issues and questions arise from this research.

Snodgrass (1989) asks 'How many memories?'. This question was originally asked by Tulving (1985) but Snodgrass developed a memory arrangement based on 3 types of memory tasks. The first is called 'episodic' memory which is essentially 'remembering that' something had occurred or that something was said. The memories reflect traces of autobiographical events, important to the individual and retained by the individual because of some relevance pointer. The second memory task is that of 'semantic' memory or 'knowing that' something is true or false or something is known or believed to have occurred. This type of memory is more encyclopedic and is indexed by a number of conceptual pointers so information is retained because it points to some other piece of information. The third memory is that for 'knowing how'. Snodgrass describes this memory as a 'procedural' memory in that what is retained is a perceptual/motor sequence of actions which have been acquired and demonstrated by completing actions, by doing.

The concept of multiple memories suggests that events, occurrences and information are, in some manner and form, 'retained' by the individual in different memory 'locations'. The processes of representing and retaining information in each of the three memories are considered different tasks, but Snodgrass admits to knowing little about the degree of independence or interdependence among the memory types. The concept of different memories also brings up other questions: under what circumstances are the different memory tasks activated (eg. recall, cued recall, recognition tasks), how is information in each memory represented, and what processes are used to access the different memories? Answers to these questions may lead directly to processes which may be supported in the knowledge engineering process.

4.2 Environment X Memory Research

Smith (1988) presented anecdotal evidence for episodic memories which were cued or triggered by environmental stimuli. Bjork and Richardson-Klavehn (1989) present research on the context-memory relationship directly. They studied aspects of various contextual influences on how information is initially retained and how information is available, based on contextual retrieval cues. They contend that generating ideas or becoming aware of new information is done within a defined, current, episodic context. Features of the context are

incorporated with the new information in memory. Recall probabilities are seen as a function of the strength of association to the current context. Matching episodic contexts ensures better recall of information.

It is necessary also to distinguish between aspects of the episodic context that are meaningfully related to the information retained and those aspects of the context which are independent and incidental to that information. Baddeley, (1982) distinguished 'interactive' and 'independent' forms of contextual information or patterns. 'Integrated' and 'isolated' distinctions were made by Eich (1985) and Hewitt (1980) categorized contextual patterns as 'intrinsic' or 'extrinsic' to the meaning of the retained information. Bjork and Bjork (1988) proposed three aspects of context. That information which was clearly and strongly associated with the target information was labelled 'integrated' information. 'Influential' information was that which had strong associations to the target information in the sense that it influenced the degree of meaningfulness of the target information. "Incidental' information was not only independent or isolated from the target information but did not influence the interpretation of that information. These three distinctions are used to describe context-target relationships. Finally, these researchers postulate two types of cognitive processing during recall of information. The data driven process (also see Jacoby, 1983) posits a type of task which forces the individual to respond to perceptual information only (eg. identify words or word fragments or supply missing structures). This is usually considered an indirect form of memory. Conceptually driven tasks (see Roediger and Blaxton, 1987) demand constructive, semantically-based processes as a basis for direct recall of information. These three main dimensions (concept-target relationships, type of context, and type of recall task) form a taxonomy of recall which suggests 12 different methods of structuring a recall situation to increase the effectiveness and efficiency of recall activity.

Memory recall situations are common ones in knowledge engineering activity in the knowledge acquisition phase. The concept of multiple memories has application (eg. La France, 1986) in that structured recall situations established by the knowledge engineer affects the retrieval processes of the expert. Also, structures such as the Bjork and Richardson- Klavehn's taxonomy and can act as a basis for developing support tools and procedures to aid in recall for the expert, the knowledge engineer and even for the user.

4.3 Retrieval and Organizational Strategies

Kolodner (1984) outlines a number of principles of memory retrieval and storage. Those of particular interest to knowledge engineers are presented and discussed. The first principle states that human remembering is often a process of re-construction. An individual must re-assemble or recreate the necessary structures and events which 'must have happened' rather than directly retrieving what actually did happen. The 'actual' event, with all its salient features, is not 'stored' in memory. When asked to recall a situation, an individual will produce a cogent assembly of plausible items. A second principle suggests that the process of remembering mirrors a progressive narrowing or focusing-in on a description of the recalled event. In other words, an individual begins with salient features (as perceived in the recall context) and begins a type of choice or selection task in order to eventually select the full event (for reconstruction) to meet the current recall demands (eg. E-MOPS are considered by Kolodner to be the basic structures which organize events in memory).

The issue of contextual information is raised in a third principle. In order to retrieve the appropriate information from memory, an individual first requires some information or knowledge about the contexts associated with the target items. The original context is seen as having a powerful link with other salient features of information (previously discussed). A fourth principle suggests that retrieval often requires a search for something other than

what was requested. In order to successfully retrieve and re-construct an event or episode, it is often necessary to locate intermediate or ancillary information which may act as indices for the required information. Finally, a fifth principle suggests that conceptual categories contain or hold generalized information only and that details may be generated at the time of recall.

Each of these principles raise issues of interest for the knowledge engineering environment. Naive assumptions about what an expert offers in response to questions lull the knowledge engineer into believing that he/she has 'captured' the necessary knowledge from the expert. Tools, techniques and procedures based on these principles may aid the knowledge engineer to clearly identify what knowledge has been gained, what further knowledge is necessary and what knowledge is suspect. The effects of the knowledge engineer's questions are not studied yet this process is the main method for gathering expert information.

A more detailed analysis of retrieval processes is necessary to identify supportable processes. Kolodner (1984) suggests two main types of retrieval activity. Processes for constructing and further specifying the context for search represent the first type. She calls these processes 'executive' strategies. 'Instantiation' strategies represent the second type of process. These processes direct search and the application of constructive strategies. Elaboration, transformation, and relation have been identified. One event may enable another, act as a precondition for another, may result from another, act as a reason for another. An event can be linked to another event in a larger episode of events, related in a sequence of events, act as a preceding or following event or act as a standard event. Similar relationships have been distinguished by Schank (1975) and by Graesser and Clark (1985).

Kolodner (1984) also discusses the important aspect of event 'features'. These features are aspects of events which are associated with the target information and unique features usually make the best indices for memory retrieval strategies. Also, good features are able to relate events and provide context relationships. The indices are then used for searches. Access to information retained by an individual can be more efficient through the use of key features. One method of retrieval is through responses to questions (eg. Lehnert, 1978) which are based on key features and which emphasize the appropriate format or form of the answer as opposed to the content of the answer. Good answers are seen as responding to the intent and content of the question. Using the model of instantiations (Kolodner, 1984), experts may be given tasks where they are required to identify a variety of relationships between events as well as the features of events.

Transformational processes Kosslyn (1980) themselves deserve a closer look for their particular relevance to knowledge engineering. In contrast to comparison processes, which juxtapose memory structures and return a match/mismatch or measure of similarity, transformational processes change the contents of a structure. 'Alterations' are one form of transformation which add or delete structures or parts thereof or they act to reorganize the structure. 'Productions' use old data structures to generate new structures or replace old ones. 'Derivations' are new structures which have been generated by inferential processes.

The preceding discussions of retrieval and organizational processes have reflected a set of 'content-free' processes. Retrieval processes based on semantic meaning also provide a basis for understanding how some structures are implicitly activated. The basic assumption (Nelson, 1979) is that words are tokens which are connected to a larger number of related concepts but that these concepts can be connected to a larger number of related concepts. Hitting the trigger activates a network of concepts. The questions arise, however, as to what information is actually stored and can be activated quickly (implicitly) and what must be re-generated. Graesser and Clark (1985) have reported that some semantic forms of

knowledge are not likely to be stored (see section on text comprehension). For implicitly activated concepts, the cue 'set' is of great importance. The larger, more diverse, the set of cues, the greater the network of related entities and the greater the time and confusion in re-generating the unstored information. A complex stimulus triggering multiple representations in memory can lead to a wealth of information but the representations themselves may be of a different form and structure (Snodgrass, 1989; Collins and Loftus, 1975).

Do our knowledge engineering methods attempt to access different memory structures and do they support an understanding of how these structures may change during the knowledge engineering process ? Our borrowed tools, techniques and procedures were not generally developed with an understanding of memory structures and processes in mind. Also, the issue of context-memory relationships has been neglected even though its effect is of great importance to knowledge engineering. An understanding of how new structures are developed and incorporated into new episodic experiences or how related concepts become incorporated into representations is not supported in knowledge engineering tools. Determining which concepts are related directly and which indirectly to decision making are of concern to the knowledge engineer but the tools used are rudimentary and are focused on the knowledge, not the processes.

5. Text Comprehension

5.1 Cognitive Processes in Text Comprehension

The reader appears an active participant in text comprehension. Perceptual processes (processes which react to visual stimuli and which reflect modular stimulus processing) occur during comprehension and are considered mandatory, automatic and immediate (Swinney and Osterhout, 1990). Cognitive processes, on the other hand, reflect inference processes based on prior world knowledge, plausibility, and pragmatics. The cognitive activity drives analysis and acts as the basis for viewing readers as constructive learners (Wittrock, 1979) or 'active agents' (Anderson, 1970). These cognitive processes and their influences are of interest to better understand the cognitive demands placed on the knowledge engineer.

Inferential processes constitute a class of cognitive processes used in text comprehension to understand concepts, to differentiate between concepts, and to make connections between and among concepts. As someone reads, he/she attempts to make the text meaningful, usually by making predictions (Smith, 1982) and then by determining if the predictions hold true. The elimination of possible meanings until the correct one is found is a process of inferencing based on prior knowledge and on the goal of the reader (van Dijk and Kintsch, 1983; Lesgold and Perfetti, 1978). These types of processes are of interest to us because to make meaningful the information contained in domain textual material, onerous inferential demands are placed on the knowledge engineer.

It is very common for readers to fail in making all the necessary inferences during text comprehension (Britton et al, 1990). Comprehension failure increases as the text becomes less of a narrative, with common inference patterns, and more expository. It is common for a knowledge engineer to read expository and or instructional texts. Making the appropriate inferences depends in large part on prior knowledge of the domain, so considerable inferential demands are placed on the knowledge engineer. The more inferences required of the reader by the text, the less likely the inferences will be made and the less likely the meaning captured. Making the necessary distinctions of concepts and making the necessary inferences of these concepts requires familiarity with the domain: something which the

knowledge engineer does not initially have and may never develop sufficiently during the knowledge engineering activity of the project.

5.2 Inference Making During Text Comprehension

Content-based inferences are those which can be made on the basis of perceived word meaning (semantics), as the word is used in the sentence (syntax), or in the context of understanding (pragmatics). Seifert (1990) distinguishes three types of inferences: anaphoric inferences or inferences based on pronouns (see Clark and Haviland, 1977), instrumental inferences or inferences about action (see Singer, 1980), and pragmatic inferences or contextually driven connections (see Graesser, 1981). These three types of content inference are generated on the bias of the kind of world knowledge (and specific domain knowledge) needed to understand a certain kind of text.

Thematic inferences (Seifert et al, 1986) and schematic structures (Schank, 1982; Schank and Abelson, 1977; and Rumelhart and Ortney, 1977) are those inferences generated less on the basis of content and more on the basis of abstract patterns of goals and plans suggested by the text (Seifert, 1990). The relations between concepts are implied more by an abstract conceptualization or structure than by the semantic links in the text. In many cases, these themes are determined by the processing goals (Holyoak and Novik, 1988) of the comprehender. Skimming a text vs searching a text for a specific point may lead to different inferencing paths (Seifert, 1990). The processing goals of the knowledge engineer may vary at different points in the knowledge engineering process (i.e. during each pass through the text). Misconstruing the meaning, generating incomplete or erroneous inference paths, and selecting or constructing partial or incomplete thematic and schematic structures hampers the knowledge engineering process.

The difficulties of the knowledge engineer are further defined by Garner (1985) who notes that the comprehension of technical, expository prose is "little assisted by content-schematic knowledge, in that the very novelty of the material ensures that the readers will be unable to fit much of the new information into their old in-head information"(p.10). Van Dijk and Kintsch (1983) suggest a series of comprehension stages for technical prose. The first step involves a focus on specific content (based on single, individual propositions) to build a 'microstructure. Then, the task is to produce or derive a 'macrostructure' of important content through the application of three types of inferencing rules - deletion, construction and generalization. Procedures for supporting this set of inferencing activity may help overcome the need for domain knowledge in initial comprehension activity.

Types of content-based inferences are more dependent on stored knowledge than on generated or infered knowledge. When reading technical prose, comprehension is strongly based the capacity of the reader to make the correct content-based inferences. Knowing what types of structures are usually stored versus those that are usually generated from stored information helps in determining what processes may be constructed to aid the knowledge engineer. Graesser and Clark (1985) have reported a systematic study of those structures which appear to be stored and those which are not. Those concepts that are known to be directly stored may be elicited. Those concepts can then act as anchors to derive those concepts which have not been directly stored. Knowing which concepts are likely derived gives the knowledge engineer the opportunity to challenge, test or validate them in another manner. Different processes are also necessary for eliciting different types of concepts (eg. causal, goal).

Causal inferences are also of interest. Myers and Duffy (1990) describe a popular mechanism for the development or generation of causal inferences during text comprehension. First, a network representation is constructed. This network results from

those initially identified concepts in the text. Tentative relationships are constructed on the basis of the surface meaning of the text. Sets of inferences are then generated from these antecedents and they become part of the network. More inferences are drawn as more related information becomes available through more text. In particular, causal antecedents are believed held in short term memory awaiting a link or connection to another concepts which satisfies causal chain properties (Fletcher and Bloom 1988; Trabasso and Sperry, 1985). These causal inferences display four particular properties (Trabasso et al, 1989). The first property is 'temporal priority' in that a cause never happens after the effect. The property of 'operativity' states that the cause must be active at the time when the consequence occurs. The third property suggests that a cause must be seen as necessary for the event to occur. Finally, given a set of antecedent conditions, a cause must be 'sufficient' for the consequent to occur.

For text comprehension in knowledge engineering, it is important for the knowledge engineer to generate the appropriate causal inferences while reading the text. However, given the complexity and newness of the content in the domain, it is entirely likely that the knowledge engineer will fail to make the necessary causal inferences. Some research findings (Graesser and Clark, 1985; Liu, 1989; Trabasso et al, 1988) suggest that it is possible to improve text comprehension by inviting causal inferences by such procedures as systematically posing questions to the reader. Procedures which flag the need for a causal inference or to identify when one is missed would aid the knowledge engineer during comprehension.

5.3 Role of Text Structures in Comprehension

Grammatic and semantic structures in the text have been shown to influence text comprehension. Rumelhart (1980) suggests that when text comprehension is appropriately completed, it is done so because structures in the text have helped to organize knowledge into units which activate the required cognitive processes so that new information is easily processed. When comprehension fails, it is partially due to the reader not having the appropriate schemata for the text content; the reader having the appropriate schemata but no textual cues to trigger its generation or retrieval; or, the reader finds or constructs a consistent interpretation of the text but not the one which was intended (see also Spilich et al, 1979).

Haberland and Graesser (1990) have found that when goal hierarchies were easily portrayed in the text passages subsequent statements were easier to comprehend. When readers are forced to assume or identify goal hierarchies on their own, there tends to be a greater failure rate in making the appropriate inferences. Poor text construction leads to poor text comprehension in a number of other ways as well (Garner, 1988):

Expert generated text comes in many forms. Highly structured text often reflect assumptions that the reader has the necessary background knowledge for sufficient comprehension. In this type of text, goal hierarchies and cause-effect indicators may not be as prevalent as they may be in more introductory material. Procedures which flag these types of indicators in richly technical material (Woodward, 1990) support the knowledge engineer's inferencing processes.

5.4 Meta-Cognition and Comprehension Failure

Comprehension of technical, expository text can also be affected by factors or cues external to the text (Rothopf, 1982). Metacognition, or stable knowledge the reader has about him/herself, about the comprehension task, and about the strategies employed affect the success of comprehension. Flavell (1981) identified four metacognitive components and

their relationships to success in text comprehension. Meta-cognitive experiences of the reader refer to those thoughts of how the reader is approaching the goal of reading, questions about how the comprehension is progressing, or the intrusion of other thoughts into the comprehension process. Cognition 'goals' refer to the variety of reasons for reading (eg. skimming, identifying assumptions). Finally, the cognitive strategies of the reader refer to the types of processes the reader uses while reading the text (eg. highlighting passages or writing down key words). Steinberg (1984) offers a compendium of cognitive processes which may be used during text comprehension.

Another critical meta-cognitive process for a reader is that of detecting comprehension failures (see Baker and Brown, 1984a, 1984b; and Brown et al, 1986 for reviews). Often readers do not pay attention to all the words of a sentence or passage. Also, sentences are often mis-parsed due to a partial match between text-based terms and the relevant knowledge structures (Reder and Cleermans, 1990; and see also a summary of error detection research, Garner, 1988). Finally, the necessary inferences may not be made by the reader. Under these circumstances, comprehension will be incomplete and the reader may fail to note the discrepencies. Comprehension failure can only be rectified or corrected if the reader becomes aware of the errors or aware of the partial nature of the inferences. If detection fails as well,then few connections or inferences are likely to be made. Markman (1977) has called this state of affairs the 'delusion of comprehension'.

5.5 Summary

Most of the research in natural language processing in the field of knowledge engineering addresses the understanding and use of natural language as a basis for knowledge acquisition for knowledge-based systems. Wetter and Nuse (1992) have identified many conceptual and practical difficulties with this approach. Essentially, text-based information used for knowledge engineering purposes is removed from its pragmatic context. Knowledge structures present in the pragmatic context for writing the text may or may not relate directly with the knowledge structures in the domain or with the pragmatic context in the knowledge engineering domain. The resulting formal knowledge has experienced two critical transformations: the domain knowledge into natural language and the natural language into a formal language. This approach to natural language focuses on generated knowledge structures and their relationship to domain knowledge.

This paper suggests an alternate, but complementary, approach to the used of text-based natural language by suggesting the development of tools, techniques and procedures which aid and/or identify the cognitive inferencing processes during text comprehension. Rather than focusing on 'extracting' the knowledge from natural language, the focus is on identifying and supporting the cognitive processes involved in knowledge engineering activity. There appear to be well defined and substantiated processes which can focus tool, technique and procedure development.

6. Judgment and Choice

6.1 Judgment and Choice in Knowledge Engineering

Making judgments and choosing alternatives are complicated and complex processes. In many cases, humans complete these complex processes quickly, with less than complete information, and with little consideration of their own thought processes. Limited human information processing capacity requires that we reduce the complexity of the information environment by a number of methods, which consequently result in loss of information and meaning. The expert's domain displays its own inherent patterns but the knowledge

engineer and the expert (and the user) structure their own patterns for the domain to make evaluative and predictive judgments and to deal with their own uncertainty about the patterns displayed by the domain.

A common type of judgment made in knowledge engineering is that of 'probable cause'. Einhorn and Hogarth (1981) have identified a number of factors which affect this type of judgment. Aspects of the context in which the judgment is made is considered a major factor. The causal context sets the stage for how various causal candidates emerge as distinct from the entire causal context. Causal clues such as temporal order, co-variation, contiguity in time and space, and the similarity of cause and effect reflect a number of imperfect indicators of causal relations which influence judgment. A third major factor is that of the judgmental strategy used to combine the information from the causal context with the causal clues. A final factor is the role of alternative explanations which may act to discount or reduce the strength of particular causal patterns.

Probability theory has been used as a contrast point to human causal reasoning processes. Tversky and Kahneman (1980) have shown that 'base rate' information is often ignored when making predictive judgments unless it is seen as relevant in the causal context. Judgment errors such as reversing the probabilities of two related events (Eddy, 1982) have also been identified. Issues of plausibility of combined, predicted events present the effects of taking multiple connected predictions into account (Kahneman and Tversky, 1973; Slovic et al, 1976). Accurate judgments become scarce as multiple predictions are requested. Finally, research has shown how people update judgments upon receiving new information (Edwards, 1968). When new information forces a review of a prior judgment, it has proven difficult to evaluate the new evidence against two alternative hypotheses, especially when one has not been well specified. When updating beliefs (Fischhoff and Beyth-Marom, 1983), it is not common to make simultaneous evaluations of that evidence for all alternative hypotheses.

The interaction effects between task demands and human judgment processes helps explain some of the difficulties individuals have with making judgments under certain circumstances. Cue availability constitutes one contextual variable reflecting aspects of task demand (Hogarth, 1987) which strongly influence predictive and evaluative judgments. In the knowledge engineering domain, judgments are made by the expert, knowledge engineer and the user. Availability of appropriate cues (Tversky and Kahneman, 1973) can affect judgments of relative frequency and information presentation patterns can affect the salience of context and cues. Often the degree of variability of a variable is strongly distorted by contextual effects, thus affecting resulting judgments. For example, people tend to base their estimates of frequencies and probabilities on absolute vs relative frequencies (Estes, 1976)

Within the knowledge engineering domain it is possible to identify and outline those judgment processes which are not normally completed effectively by the expert, knowledge engineer and the user. Statistical models have been developed or adapted (Meyer and Booker, 1991) but other types are possible. Hogarth (1987) has described different methods for combining information to stabilize judgment processes. Processes of judgment and choice are viewed as conflict resolution models in that the selection of competing alternatives requires a resolution of conflicting information. 'Compensatory' models directly address the conflict created by the differences by allowing trade-offs on the choice dimensions. Examples are the linear model, additive difference model, and the ideal point model. Each model sets a tactical approach to combining information. 'Non-compensatory' approaches are those which do not allow trade-offs on choice dimensions. Examples of these types of models are the conjunctive, disjunctive, lexicographic, and elimination-by-aspects models.

The field of decision analysis focuses on identifying the intellectual tasks required for making decisions and the field has developed a variety of mathematically and logically based theories, procedures and techniques. This approach stresses the organization of information in a manner which is more conducive to making correct judgments and decisions. A main problem is figuring out what the information means and what relevance it has to the decisions under investigation. The intellectual tasks are identified as systems analysis or decision analysis. The main steps are to identify the problem (its overall analytic structure) and to formalize parts of it. Secondly, the analyst picks an appropriate subset of analytic tools and structures. Finally, the elements and relations identified in the first step are refined (von Winterfeld and Edwards, 1986).

Based on this approach, a number of techniques and procedures have been developed to aid decision making. Decision trees identify steps, sequences of judgment points, and the possible paths (see Holloway, 1979; Behn and Vaupel, 1982). Event and fault trees are similar techniques. Influence diagrams (Howard and Matheson, 1980) present a graphic picture of interactions of variables in a model without imposing a tree structure. The study of uncertainty measurement has also produced a number of models of how to model and represent uncertain information (eg. value and utility measurement, group probability assessments). Finally, this approach has spawned such techniques as multiattribute utility theory (Edwards and Newman, 1982) and sensitivity analysis (von Winterfeld and Edwards, 1986). Techniques in knowledge acquisition based on a decision analysis approach have been developed (Bradshaw and Boose, 1989a; Bradshaw et al, (1989b).

6.2 Judgmental Bias and Decision Aids

Hogarth and Makridakis (1981) have listed a number of sources of bias and have identified their effects on judgment and decision making processes. In the information acquisition stage of decision making, cue clarity and availability, selective perception, cue frequencies, concrete information domination, illusory correlations, data presentation form (primacy, recency, mode, mixture, display and context), and framing are listed as sources of bias. In the processing stage of decision making, inconsistency (of strategy application), conservatism (low revision), non-linear extrapolation, heuristics, anchoring and adjustment, representativeness, law of small numbers, justifiability, regression bias, 'best-guess' strategy, complexity of relationships, emotional stress, social pressures, and inconsistent information sources are identified as sources of bias. In the output stage of decision making, question format, scale effects, wishful thinking and illusion of control are seen as biasers. Finally, in the feedback stage, incomplete outcomes, misperception of chance fluctuations, success/failure attributions, logical fallacies in recall and hindsight bias contribute to faulty judgments.

Specifically in the knowledge engineering environment, Meyer and Booker (1991) and Cleaves (1986) have identified expert bias under two categories: motivational and conceptual. Cleaves developed a number of monitoring and corrective procedures for use with experts to reduce bias. 'Mechanical' procedures manipulate the task or adjust the judgments after knowledge elicitation. 'Behavioural' procedures use interviewing and group interaction techniques to encourage full understanding, identification and control of biasing processes. Visual props to emphasize visual patterns rather than verbal expressions, varying the format of the requested judgment, using differences between actual and essential values, and combining judgments from several individuals constituted mechanical means of bias reduction. Behavioural means included focusing on specific biases in interviews, breaking down complex relationships, training experts in the types of biases, exhorting experts to give reasons for judgments and using group settings for developing consensus. Meyer and Booker (1991) developed similar methods to reduce

elicitation biases and they have developed a variety of statistical methods for combining judgments and for reducing biasing effects with groups of experts.

7. Social Cognition and Communication

7.1 Effects of Domain Content on Cognitive Processes

In scientific and technical domains judgments are based on ideas, concepts and/or concrete objects. Using concepts and ideas about concrete entities or well established principles and laws requires a set of cognitive processes or inference processes as a basis of making decisions about something external to the decision maker him/herself. In social domains where decision making needs to include judgments about people a different set, or perhaps an additional set, of cognitive processes come into play. In domains such as law or banking, judgments are made by people about other people. In addition to inferences about ideas, concepts, concrete objects, inferences are made about intentions, characteristics, and motivations of people. This section presents a sampling of research from the areas of social cognition and communication and addresses its application to knowledge engineering. Knowledge engineers may make social decisions about the expert and/or the user. The expert makes social judgments about the knowledge engineer's abilities and extent of domain knowledge. If the expert's domain involves making judgments about people then social cognition processes also come into play in the expertise. In this sense, then, the social characteristics of the domain affect the types of cognitive processes involved in decision making.

7.2 Causal and Dispositional Attributions

This area accounts for a full 11% of all social psychological research (Kelley and Michela, 1980), consequently, a wealth of models and a strong theoretical foundation exists for this area of social cognition. With respect to the knowledge engineering domain, this field of research addresses the question of how the expert, knowledge engineer and user infer a correspondence between observed behaviour and the intentions that produced it. Correspondent inference theory (Jones, 1985) provides a basis for understanding the cognitive processes involved in attributing intentions and dispositions. Attribution theory (Kelley, 1983) discusses those cognitive structures and processes involved in attributing cause.

Kelley (1983) offers two sets of inference processes and structures which account for how people arrive at causal attributions. The first assumes there is information from multiple sources and that covariation of an observed effect and possible causes can be perceived. The second assumes that the perceiver is faced with a single observation and must then use the configuration of factors that are plausible causes of the observed effect. This first set of processes is named the 'covariation' principle. Kelley likened this set of cognitive processes to an ANOVA analysis. 'Consensus' information is required in that the number of people who make similar decisions is taken into account in the decision making processes. 'Consistency' information about how often the single decision maker in question made similar judgments under similar conditions is used as well. Finally, information concerning the 'distinctiveness' of the choice which provides a sense of whether or not a different choice is made due to small changes in one factor. If each of these three factors is considered as having two values (high and low), then a 2 X 2 X 2 ANOVA pattern helps explain this principle. Shaver (1981) points out however, that this approach does not help in distinguishing the truly causal from covarying but non-causal relationships and Langer (1978) has suggested that causal attributions are elicited by types of questions and context demands and are not usually emitted.

The second set of processes describes the 'configuration' principle. This principle bases its strength on proposed underlying structures or causal schemata to help explain casual attributions. Fiedler (1982) points out that a causal schemata does not really exist but it acts as a useful psychological construct for explanation and prediction. One schemata is that of Multiple Sufficient Cause which is evoked when the decision maker can predict effects from the presence or absence of causal contenders. Depending on the presence or absence of multiple contenders, this schemata helps to sort out and order the various combinations of causes. Two important principles are connected with this particular schemata. The 'discounting' principle outlines when one cause or set of possible causes has sufficient strength to discount others. The 'augmentation' principle outlines under what conditions causal contenders support one another.

Schemata of this type support decision making when information is incomplete, when causal 'shorthands' are required for complex situations, and when similar decisions are required across different content areas (Fiske and Taylor, 1984). Reeder and Brewer (1979) postulate 'implicational' schemata to refer to the perceiver's prior conceptions about categories of behaviours. 'Partially restricted' schemata reflect extremes of behaviour. If a person's behaviour is seen as an extreme type of behaviour then it is difficult for the person to be seen acting in the opposite extreme. 'Hierarchically restricted' schemata assign a behaviour or individual to a category which keeps the individual from being seen as better or worse that than category. For example very skilled people experience a range of outcomes depending on motivation and task demands but low skilled people are never seen as having greater aptitude or skill. 'Fully restrictive' schemas are categorical attributions which identify stable levels of an attribute (eg. neatness).

Other research has supported the free occurrence of causal attributions. This research applies to knowledge engineering activity. Lau and Russell (1980) devised a method for identifying attributional structures through content analysis of newspaper stories. Think aloud protocols were analyzed for causal attributions from the responses of parole decision makers while they were reviewing cases (Carroll and Weiner, 1982). During problem solving, when prior expectations were not confirmed, the causal attributions made by subjects were identified and analyzed (Pyszczynski and Greenberg, 1981; Hamilton, 1988).

7.3 Cognitive Components of Causal Attribution

In the previous section the structures of attribution were presented. This section reports on the research which identifies the processes of attribution. The logic of attributions is addressed, the inference processes as well as the knowledge used when making causal and dispositional attributions is summarized.

Hansen (1985) distinguishes attributional content from process. Concepts like covariation and configuration (causal schemata) are considered aspects of logic. How the actual attributions are made constitute the process (see also Newscombe and Rutter, 1982a, 1982b). The knowledge structures used when making attributions is seen as the content (see also Galambos et al, 1986). Kelley's (1983) covariation model has been contrasted with Hewstone's and Jaspars (1987) logical model for identifying necessary and sufficient conditions for causal attribution. The logical model helps delineate all possible combination of causes for consideration. The 'abnormal conditions' model identifies 'counterfactual' criteria and 'contrastive' criteria to establish an opportunity to compare the normal to the abnormal.

Cognitive processes for causal attribution are based largely on the research exemplified by Tversky and Kahneman (1980). Attributional heuristics for causal information processing

such as representativeness, anchoring and adjustment, and availability have been identified and are discussed in more detail in another section of this paper. The concept of attributional salience is addressed by Taylor and Fiske (1978). This work identifies the process by which causal attributions refute judgments based only on immediately perceivable information. The mechanism suggests that this type of information can become overly represented in subsequent explanations. In other words, new information which is drawn directly from the immediate context may, under certain circumstance, become over represented in subsequent explanations and render a prior attribution null and void.

Causal schemata are assumed to affect perception, memory and inference (Fiske and Taylor, 1984). They are viewed as working in a top-down manner to simplify and/or amplify information and they act to identify salient information for attributional processes. Knowledge-based causal attribution (Abelson and Lalljee, 1988; Leddo and Abelson, 1986) focuses on the content of causal schemata. This approach tries to draw distinctions between the process of explaining events and the process of understanding them. It has been found that this process requires an understanding of how an individual forms an action plan, the goals of the plan sequence, how that particular plan could be seen to achieve the goal and those particular conditions which initiate the goal (Read, 1987).

7. 4 Meaning Interpretation in Communication

Most of the work on meaning interpretation emphasizes the semantic aspect of language generation and comprehension. This approach is based heavily on the semantic qualities of memory (Kolodner, 1984). Semantically-based categories hold conceptual items which are related through inferences that can be drawn about the categories and concepts. Semantic-based meaning is coupled with words and phrases. In any context, meaning is generated through the use of stored concepts in interaction with a variety of inference processes. Frames (Minsky, 1975), scripts (Schank and Abelson, 1977), schemas (Rumelhart, 1980), mental models (Johnson-Laird, 1980, 1983), causal memory (Genter and Stevens, 1983), situation models (van Dijk and Kintsch, 1983), and E-MOPS (Kolodner, 1984) are examples of semantic memory structures and their accompanying inference processes. These semantic approaches have influenced knowledge engineering computational and representational structures.

However, Grice (1975) places the emphasis not on word meaning but on implications of utterances. In studying communication, linguistic mechanisms have remained front stage in the form of much research in phonology, syntax and semantics. These three fields have produced a number of approaches which concentrate on the meaning and knowledge structures in linguistic forms. The assumptions of these approaches state that knowledge is encoded in the utterances or with the utterances. However, semantic representations of sentences cannot be regarded as corresponding very closely to to thoughts because sentences can be used convey a great number of different thoughts (Sperber and Wilson, 1988). Semantics provide a basis for understanding some of the message but little of the meaning. Semantics do not cover the time and place of the utterance, the identity of the speaker or the speaker's intention. Semantics, as studied by the grammar, only help define the range of possibilities of interpretation. The pragmatics of communication, the interpretation of utterances, helps to choose among the possibilities.

Sperber and Wilson (1988) put forward the mutual knowledge hypothesis. In order to reduce misunderstandings and to increase the recreation of meaning between two people, the context must be shared. Does the expert assume that the knowledge engineer knows X? Does the knowledge engineer know that the expert knows that he knows X? To generate the correct interpretation of an utterance, the one intended by the speaker (Grice, 1975), every item of contextual information used in the interpretation of the utterance must be

known by both individuals and each must know that they know. The speaker and the listener must use specific strategies to interpret utterances so to identify the intent of the communication. Misunderstandings commonly occur not only because of semantic confusion but because of pragmatic confusion as well. It is critical for the knowledge engineer to establish an environment with the necessary contextual attributes to ensure that meaning is not impaired.

Without capturing the intention, mistaken facts are no different from true facts. The goal of communication, especially in a domain like knowledge engineering which demands that knowledge is understood, is to ensure that the intentions of statements are clear. When the expert gives an explanation of an event, what are his/her intentions? It is to inform, to teach, to impart understanding, is it to fill-in the background? Knowledge engineers attribute intentions to the experts and users and the experts attribute intentions to the knowledge engineers. A knowledge engineer may review written protocols for communication intentions or he/she can ask the expert for his/her intentions. In a shared cognitive environment like knowledge engineering, all participants have the capacity for making the correct assumptions about the meaning of utterances but they do not always do so. Sperber and Wilson (1988) remind us that the current task determines what information is used for communication. When situational demands trigger cognitive processes, stored information will only be used if it is necessary, the default is to use information directly inferable from the immediate context.

8. Elaborative Paths

The purpose of this paper was to develop a view of knowledge engineering as a set of cognitive processes to complement the predominant 'knowledge' perspective. Knowledge engineering was characterized as a set of cognitive activities used to understand complex, epistemologically rich domains. Selected research in the fields of text comprehension, memory, judgment, and social cognition provided examples of a variety of cognitive processes which have a high probability of occurrence in knowledge engineering activity. The question now is how can this perspective be developed and tested? What are the promising paths?

One of the basic premises outlined in section 2 of the paper described the concept of a cognitive environment. Viewing knowledge engineering as occuring in such an environment requires much more elaboration as to what constitutes such an environment. Identifying and defining the various sites of cognitive activity and the manner in which these sites interact appears to be an essential component of the cognitive basis of knowledge engineering. One of the main issues reflects the need to develop a common understanding of how meaning is produced within, among, or between interacting sites. Also, within this framework, the user of the final system becomes a much more important factor. A more elaborate and systematic description of the cognitive network of knowledge engineering is necessary.

A second path is suggested by the need to empirically identify the critical cognitive processes involved in knowledge engineering. Four likely candidates of cognitive research were presented in this paper but little evidence is available to substantiate the use of many of the cognitive processes suggested in the presented research. Also, this paper addressed only those processes attributed to the knowledge engineer, not the other cogniting agents involved in knowledge engineering. A much more systematic endeavour is required which will result in a system of cognitive processes for knowledge engineering. The various models of cognitive processes from the cognitive science research domain need to be

applied in the knowledge engineering domain to determine those which best explain the cognitive processes of knowledge engineering.

A parallel approach to the one mentioned in the previous paragraph is to test the utility of cognitve process models by developing tools, techniques, and procedures for use in knowledge engineering. This approach is a pragmatic one and may appeal more to knowledge engineers than to cognitive scientists. The development of this type of artefact would support (and may, in some cases, replace) the cognitive processes identified in knowledge engineering. The emphasis of these tools would centre on the cognitive activity in knowledge engineering rather than on the development of knowledge structures. Surveying the tools, techniques, and procedures already in use (formally and informally) by knowledge engineers and experts (even users) which could be classified as cognition-support tools would aid in this approach.

Another very critical issue raised in this paper focused on the very onerous tasks faced by the knowledge engineer when entering a new domain. The issue of how an individual deals with complexity, especially epistemological complexity, is central to the cognitive process view of knowledge engineering. Research on expertise sheds some light on this issue for the expert, but we have very little information on how the knowledge engineer and the user deal with the same complexity from a cognitive process point of view. The biomedical research presented in this paper addresses some of the same issues for knowledge engineers. Among other ideas is the importance of understanding how misconceptions develop and spread. For example, the process of comprehending technical prose might be enhanced by structuring the prose in ways which reduce the inference demands on the reader. Some clear paths for research and study have been identified but what is needed is to view knowledge engineering as a laboratory for the study of applied cognitive processes.

Finally, there appears a wealth of cognitive science knowledge available to knowledge engineers: however, challenging problems exist. The first observation is that few of the studies reported in cognitive science are in a form directly useful to knowledge engineers. This is not surprising but it is problematic for knowledge engineering. Methods are required for translating single cognitive science research results and for organizing and presenting a variety of studies into a form useful to knowledge engineers. Another related issue includes developing a valid approach to selecting relevant and promising cognitive science work for application in knowledge engineering. This development requires a thorough understanding of the theoretical foundations of cognitive science and the pragmatic demands of knowledge engineering.

Once cognitive models have been identified for translation into knowledge engineering, another serious problem arises. How does a cognitive science model produce an operational tool, technique, or procedure in knowledge engineering? Does the model retain its meaning in the new context? Does the 'engineering' alter or negate the model's meaning and application? Also, even if the result is successful, other issues arise. These issues are related to the unprincipled importing and combination of knowledge tools which may have contradictory or incompatible assumptions about knowledge. Engineering cognitive science models into knowledge engineering tools, techniques, and procedures requires a principled model or methodology of knowledge engineering.

Cognitive Science offers a great deal of well-developed knowledge to the domain of knowledge engineering but a principled, coordinated framework for identifying, selecting, organizing, translating, engineering cognitive science results into useful knowledge engineering tools, techniques, and procedures is necessary for the full benefits to be realized.

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