A KNOWLEDGE ACQUISITION ARCHITECTURE UNIFYING THE DIFFERENT STAGES OF KNOWLEDGE REPRESENTATION

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Abstract: An architecture for knowledge acquisition systems is proposed based upon the integration of existing methodologies, techniques and tools developed within the knowledge acquisition, machine learning, expert systems, hypermedia and knowledge representation research communities. Existing tools are analyzed within a common framework to show that their integration can be achieved in a natural and principled fashion that unifies different forms of mediating and intermediate representations.

1 INTRODUCTION

The overall objective of a knowledge acquisition process is to develop a computational knowledge base that is operational in that it forms a basis for automatic inference when loaded into a knowledge-based system shell. To arrive at this knowledge base, however, usually involves a major data collection activity that commences with largely informal knowledge from a wide variety of sources, and then focuses on more structured knowledge elicitation from key knowledge sources, transforming what is elicited into formal knowledge structures that form the basis of the computational knowledge base.

The management of the variety of mediating and intermediate representations involved in knowledge acquistion is in itself a major research problem. This paper seeks to address this problem directly by analyzing how the different stages of representation may be brought into a common framework.

2 STAGES OF REPRESENTATION

Figure 1 left illustrates the relations between various forms of knowledge gathered during the knowledge acquisition process and the current concept of a 'knowledge base' as composite of informal, structured, formal and computational knowledge, all linked together through dependency relations providing mutual support in explanation and ongoing development. It is this total structure that any integrated knowledge acquisition architecture has to support. There are four major paradigms underlying current tools and techniques designed to support the knowledge acquisition process itself: the use of hypertext and hypermedia tools to capture informal knowledge and begin to structure it; direct editing of knowledge in a semantic network, frame, or rule, representation; indirect elicitation through repertory grids in which critical cases are described in terms of relevant attributes; and inductive derivation of knowledge from data sets of varying quality. These paradigms, instances of their application, and relations between them are discussed in the following sub-sections. The way in which these basic paradigms are used, separately and in combination, depends on the knowledge modeling strategy adopted, and this is discussed in the next major section.

Figure 1 right shows the topics covered in this paper and some of the tools illustrating the relevant technologies discussed in each section. The objective is to show that all the different approaches may be brought together in a common framework leading to a unified architecture in which they can be combined.

2.1 Semi-formal elicitation and structuring through hypertext and hypermedia

Much knowledge is informal yet still valuable in an knowledge-based system. Text and pictures can encode and impart usable expertise, supplementing computational knowledge. Thus, the parallel development of hypertext and hypermedia is having a substantial impact on expert system architectures and knowledge acquisition tools. Figure 2 summarizes the features of hypermedia systems that need to be incorporated in an integrated architecture—the provision of capabilities for domain experts to be able to manage a database of informal material and analyze it to initiate data structure in other tools.

Hypertext-based knowledge acquisition tools have also been developed for use by domain experts to enter relevant case histories directly (Jones, 1990; Rantanen, 1990). They have also been used to support the knowledge engineer in structured analyses of interview material. For example, Woodward's (1990) Cognosys supports the analysis of protocols in terms of Graesser and Clark's (1985) linguistically derived "general knowledge structures". Other knowledge acquisition tools such as KEATS (Motta, Rajan, Domingue & Eisenstadt, 1991) have been built around a hypertext environment specifically designed for knowledge acquisition. There is also knowledge acquisition and linguistics research targeted on the direct transfer of knowledge expressed in text to structures of frames and rules (Hausser, 1989; Gomez & Segami, 1990).

Hypertext systems have been coupled to knowledge acquisition tools to provide annotation of the distinctions made and cases described which can then be used to provide explanation facilities in the final performance system (Gaines & Linster, 1990). Each item of knowledge entered through the acquisition tool automatically generates a card in the hypertext tool which is linked to that item both in the acquisition and performance phases. This card is kept up to date with the formal knowledge structures automatically, and has fields available for notes, explanations and links to text, diagrams, pictures and video sequences supplied by the domain expert or knowledge engineer.

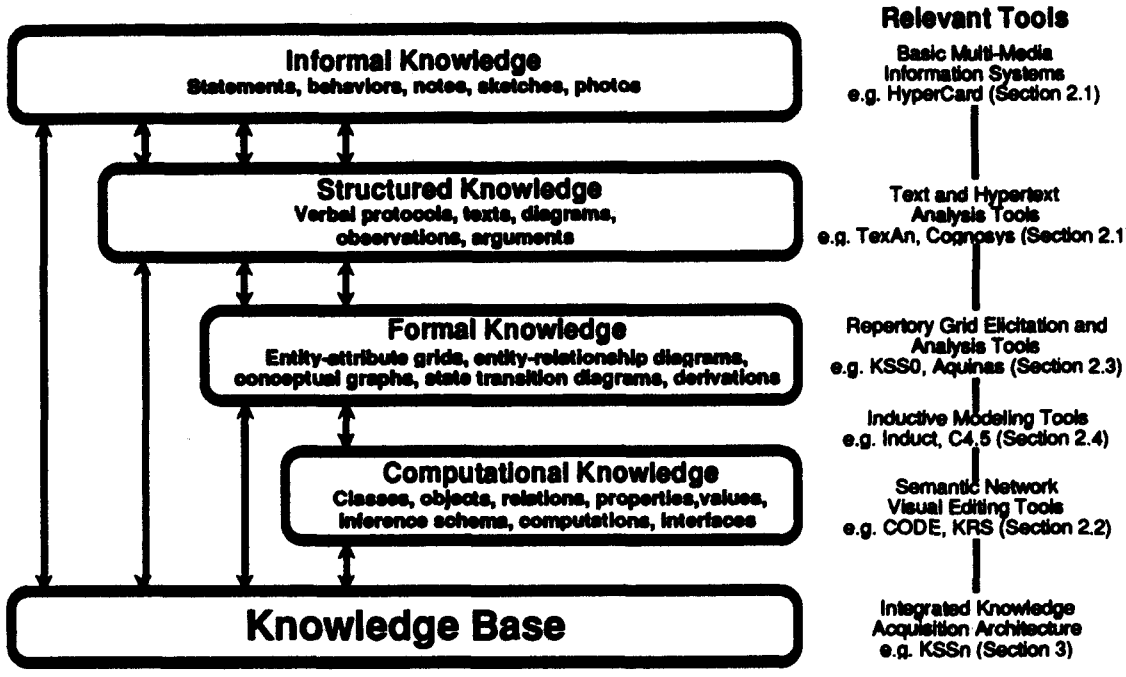

Fig.1 Knowledge acquisition for a knowledge-based system

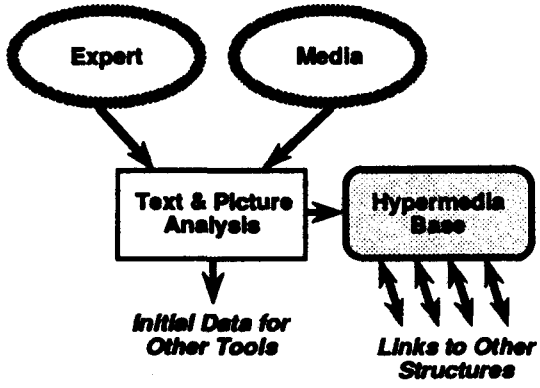

Fig.2 Hypermedia architecture

2.2 Direct editing of knowledge

Once some informal perspective on a domain has been developed as shown in the upper levels of figure 1, and domain experts have been identified, in some domains where knowledge is already overt it may be possible to move directly to knowledge modeling. Graphic editors providing direct access to semantic network representations allowing knowledge to be encoded in frames and rules provide the most common development environment for knowledge-based systems.

A wide range of knowledge acquisition tools have been developed that structure and improve the graphic editing environment, often taking advantage of domain knowledge to provide a more specific, meaningful and familiar knowledge framework to the expert. Examples are MOLE (Eshelman, Ehret., McDermott & Tan, 1987), KNACK (Klinker, Bentolila, Genetet, Grimes, & McDermott, 1987), SALT (Marcus, 1987), KEATS (Motta, Rajan, Domingue & Eisenstadt, 1991), CODE (Skuce, Shenkang & Beauville, 1989) and KRS (Gaines, 1991a,c).

Figure 3 characterizes the major features of these direct editing systems. The expert interacts through a graphic interface with an underlying semantic network knowledge representation schema which may already contain pre-encoded domain knowledge. What is elicited are:

- The distinctions that the expert makes about domain entities (attributes and relations).
- The way in which these distinctions are grouped and constrained to form major concepts.
- The entailments between concepts that constitute procedural, decision-making rules in the domain.

Older systems have less well-structured knowledge representations but Figure 3 captures the essence of recent developments in knowledge representation that are moving towards very clean, and theoretically well-founded schema.

The knowledge base of frames and rules developed in this way is then usually exported to a performance tool and validated against test case data. This generates the application loop shown on the right of Figure 3 in which the expert's distinctions lead to a description of the problem which is structured through the concepts leading to the application of the inference rules that link them.

Visual representation of knowledge structures with the potential for editing and enhancement is an attractive way of dealing with the results of other forms of elicitation, and hence semantic network editors are not so much competitors to other approaches but rather important complements to them. Thus, integration with knowledge acquisition sources as well as the capability to export to performance systems are important capabilities of any knowledge editing tool.





Structured Knowledge

Verbal protocols, texts, diagrams, observations, arguments

Knowledge Base

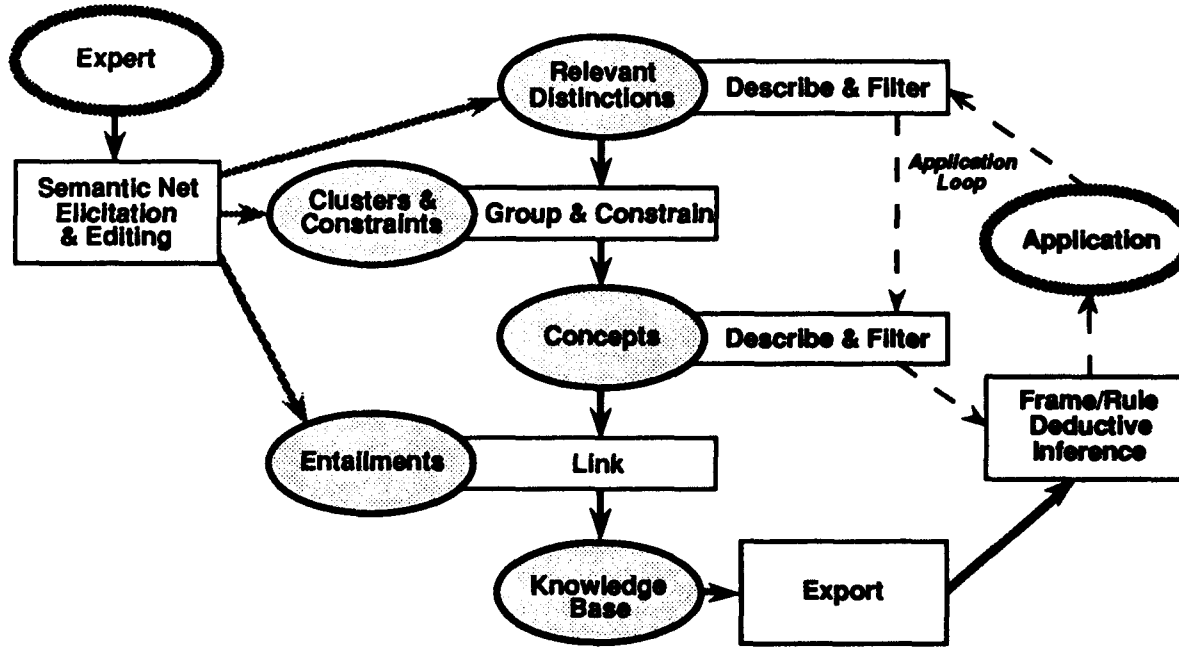

Fig.3 Semantic net architecture

2.3 Indirect elicitation through critical cases

The advantage of knowledge editing tools is that, if the knowledge is overtly available, they provide a fast and effective rapid prototyping environment for its direct capture. Other techniques assume that the nature of expertise is such that much knowledge is not so directly available. However, effective editing tools may be seen as essential bedrock to any integrated knowledge acquisition architecture. There will usually be significant sub-domains where direct elicitation is possible, and provides the fastest, most effective means of knowledge capture. There is always a need to present and make available for validation and editing the knowledge structures captured by indirect methods.

Repertory grids provide a technique useful for knowledge elicitation when experts cannot directly enter a knowledge structure. They prompt the expert for distinctions relevant to the problem domain and for critical cases that exhibit significant phenomena in the domain. The prompting is done through online analysis of the data being entered leading to feed back to the expert suggesting missing distinctions and cases. This highly focused feedback aids the expert in developing his or her mental model of the domain. It also reduces the inefficiencies of duplication and the mental blocks of psychological set, supporting rapid prototyping.

A wide range of knowledge acquisition tools have been developed that incorporate repertory grid elicitation and analysis as their major interface to the expert. Examples are PLANET (Shaw & Gaines, 1983), ETS (Boose, 1984, 1986), AQUINAS (Boose & Bradshaw, 1987), KRITON (Diederich, Ruhmann & May, 1987), KITTEN (Shaw & Gaines, 1987), and KSSO (Gaines & Shaw, 1987).

Figure 4 characterizes the major features of repertory grid elicitation systems. The expert interacts through a graphic interface to enter individuals in the domain (elements) and bipolar distinctions (constructs). Conceptual clustering techniques are used to feedback the elicited domain structure in an easily assimilated form for validation. Rule induction is used to generate entailments, or, more recently, conceptual induction as discussed in the next section to generate a default rule structure. What is elicited are:

- The distinctions that the expert makes about domain entities.
- Critical cases exhibiting the major phenomena affecting decision-making in the domain.
- The way in which distinctions are grouped and constrained to form concepts.
- The entailments between concepts as induced from the critical cases.

Older systems did not have explicit conceptual induction but left grouping into concepts or frames as a task for the export module.

The clustering and induction modules in Figure 4 are extensions of the basic repertory grid technique incorporated in PLANET and KSSO, and other major extensions have been incorporated in other tools. In particular, AQUINAS makes provision for a wider range of data types than the rating scales of the basic grid, and also allows hierarchies of cases and attributes to be specified that are related to those of semantic nets. Both AQUINAS and KSSO also incorporate tools supporting multiple sources of expertise and analyzing the relationships between different sources (Gaines & Shaw, 1989; Shaw & Gaines, 1989).

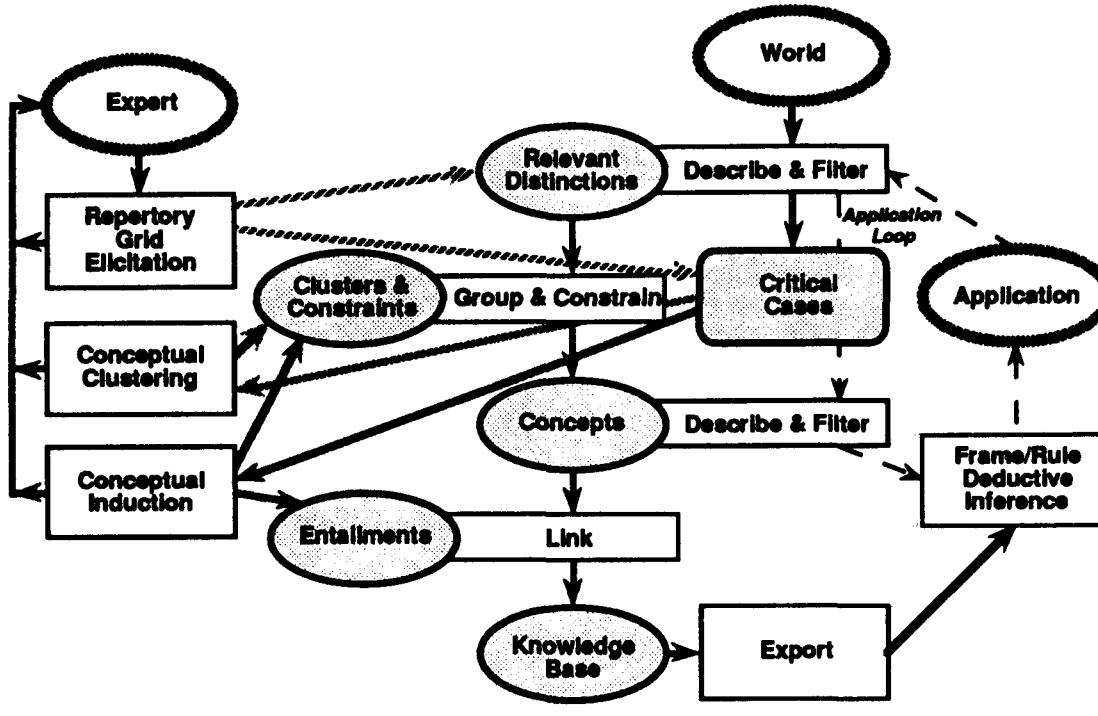

Fig.4 Repertory grid architecture

2.4 Inductive derivation of knowledge

When experts can neither directly enter a knowledge structure emulating their expertise nor enter critical cases stereotyping that expertise, they may still be able to point the knowledge engineer towards case histories that incorporate that expertise and are described in terms of largely relevant attributes and largely correct decisions. Empirical induction techniques may then be used to derive knowledge structures underlying the decisions made in these cases (Michalski & Chilausky, 1980).

The best known empirical induction methodology is that of Quinlan's ID3 which has been refined in many ways, particularly to tolerate noise (incorrect decisions), resulting in the current implementation, C4.5 (Quinlan, 1987). The original decision tree structure of ID3 based on a subsumption hierarchy of concepts with rules at the leaf nodes only is unnecessarily large in many situations, and extensions to ID3 have been developed that generate modular production rules directly, such as Cendrowska's (1987) Prism. This also can be extended to deal with noisy data as in Induct (Gaines, 1989). The extensions that deal with noisy data also make it possible to combine the decision tree and modular rule methodologies to generate default reasoning in which rules are placed at non-leaf nodes in the subsumption structure, and more specialized rules override more generalized ones (Gaines, 1991b). Such default rule structures are more compact than either decision trees or modular rules.

Figure 5 characterizes the major features of conceptual induction systems. The expert indicates a database whose designer has supplied distinctions to categorize the world and cases described in terms of these distinctions to represent it. What is derived are:

- That subset of the distinctions that are relevant to the decisions.
- The way in which these distinctions are grouped and constrained to form concepts.
- The entailments between concepts that regenerate the decisions in the database.

Classic empirical induction tools do not generate the conceptual structure but this is a fairly simple extension.

2.5 Comparing knowledge modeling techniques

Figures 3, 4 and 5 indicate strong similarities between the outcomes of direct knowledge elicitation, repertory grid elicitation and conceptual induction. This is as it should be since all three techniques are building a complete knowledge base. However, what is not apparent is the relative efficiencies of the different methodologies—that is, how large a database is required to generate the knowledge required to solve a problem? Figure 6 shows the results of one study to investigate the relationship between empirical induction and expertise transfer as knowledge acquisition methodologies (Gaines, 1989). Cendrowska's contact lens data was subjected to random distortion with known statistics to generate large datasets with a certain number of irrelevant binary attributes and a certain percentage of incorrect decisions. Induct was then run on the dataset with 5,000 items, 4,999 items, and so on, until the dataset failed to generate rules giving correct performance. This was done ten times for different datasets of the same type to give estimates of the mean and standard deviation of the size of dataset required to generate correct performance for different forms and levels of distortion.

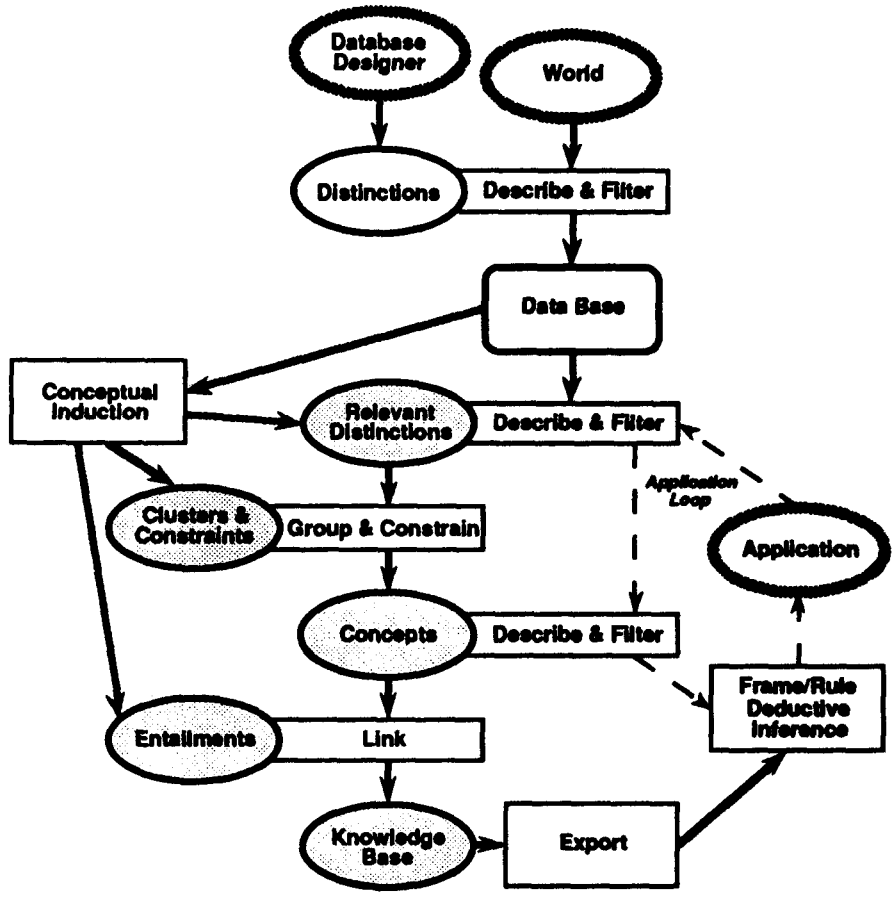

Fig.5 Conceptual induction architecture

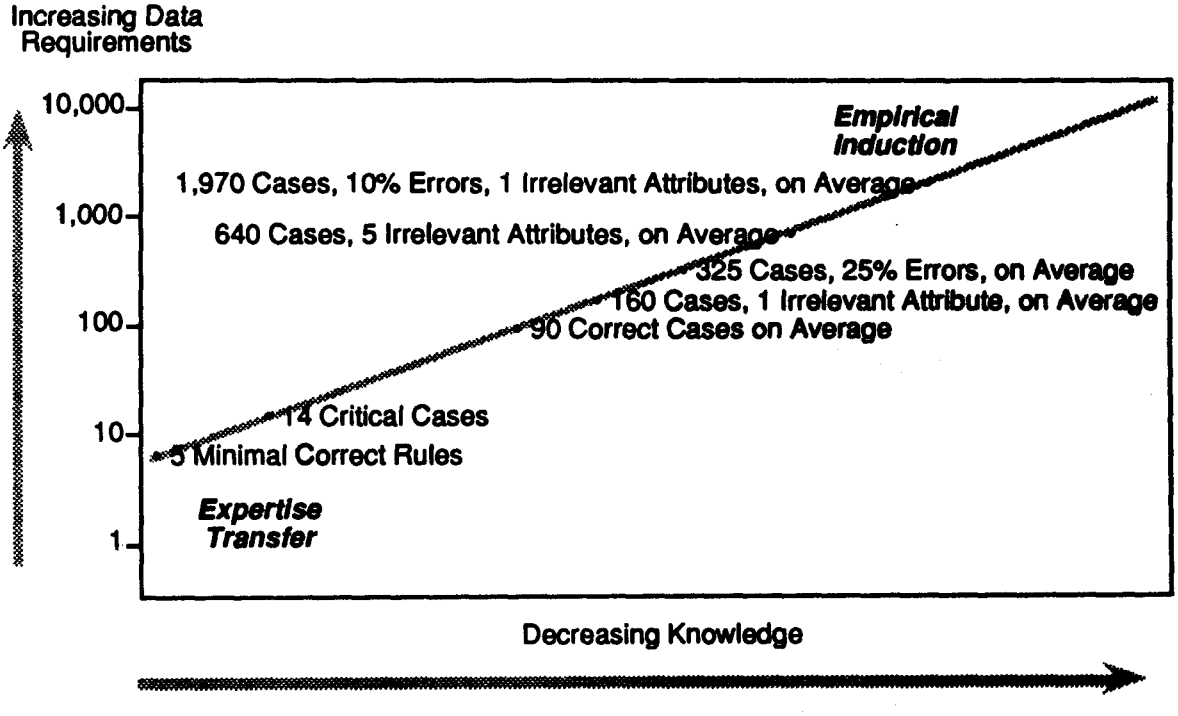

Fig.6 Data/knowledge tradeoff relating expertise transfer and empirical induction

The results shown in Figure 6 indicate the very wide range of the tradeoff between data and knowledge: from direct entry of the minimal knowledge structure of 5 default rules; through entry of 14 critical cases; through an average of 90 randomly selected correct cases; to 325 cases with 25% errors; 640 with 5 irrelevant binary noisy attributes; to 1,970 when a single irrelevant attribute interacts with a 10% error rate.

The moral from Figure 6 is not that expertise transfer is better than empirical induction, although the direct entry of overt knowledge is clearly highly ergonomic if it is available. It is rather that all three techniques described above are capable of producing equivalent quality of knowledge, and there is a continuum between them in which knowledge is traded for data.

3 AN INTEGRATED SYSTEM ARCHITECTURE

The previous section has analyzed the major types of current knowledge acquisition techniques and tools within a common framework to show their similarities and differences with a view to designing an integrated system in which they operative effectively together. The techniques described join together in the multi-stage knowledge acquisition architecture shown in Figure 7 which can be seen as a detailed implementation of the process shown in Figure 1:

- Stage ⓪ consists of developing an informal knowledge base from interviews, protocols and media.
- Stage ① consists of using the informal knowledge to elicit the major coherent sub-domains that together encompass the significant phenomena in the overall domain.
- Stage ② consists of using the repertory grid methodology in each sub-domain to elicit relevant attributes and critical cases.
- Stage ③ consists of using the conceptual induction methodology to derive concepts and rules from the grids.
- Stage ④ consists of linking the sub-domains together, generally by specifying as a constraint in one domain that some role in that domain has as value an individual in another.
- Stage ⑤ consists of testing the overall knowledge base and iterating back through any of the earlier stages in order to develop and refine it further.

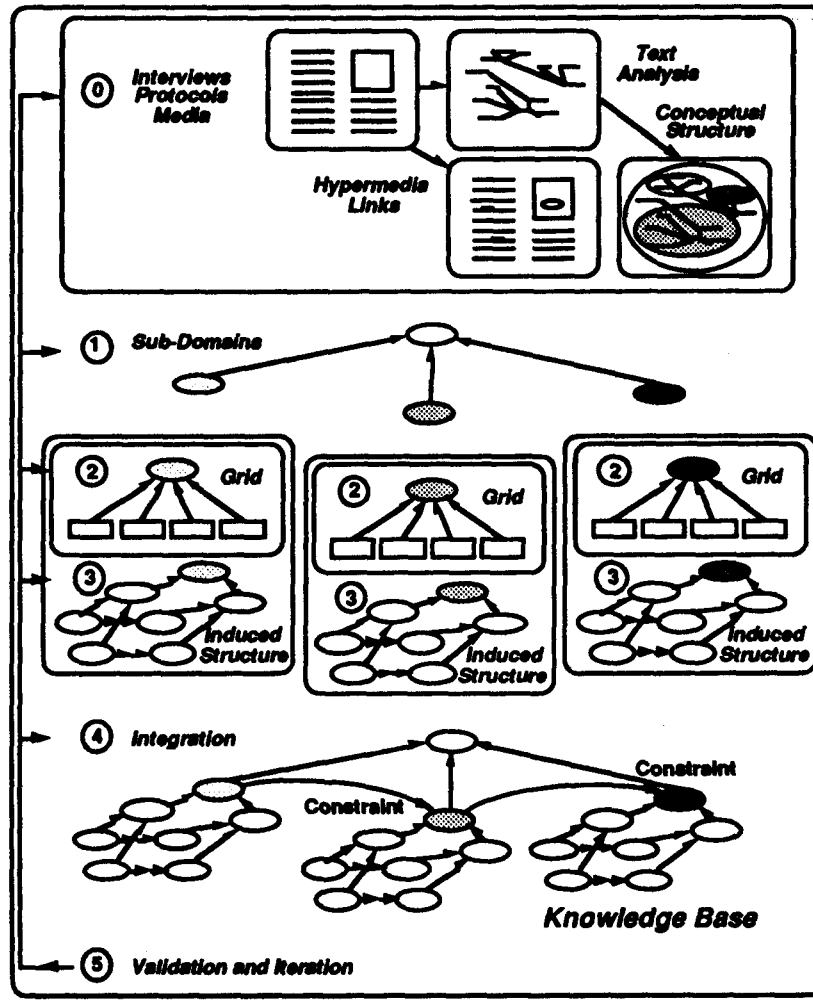

Fig.7 Integration of knowledge acquisition techniques

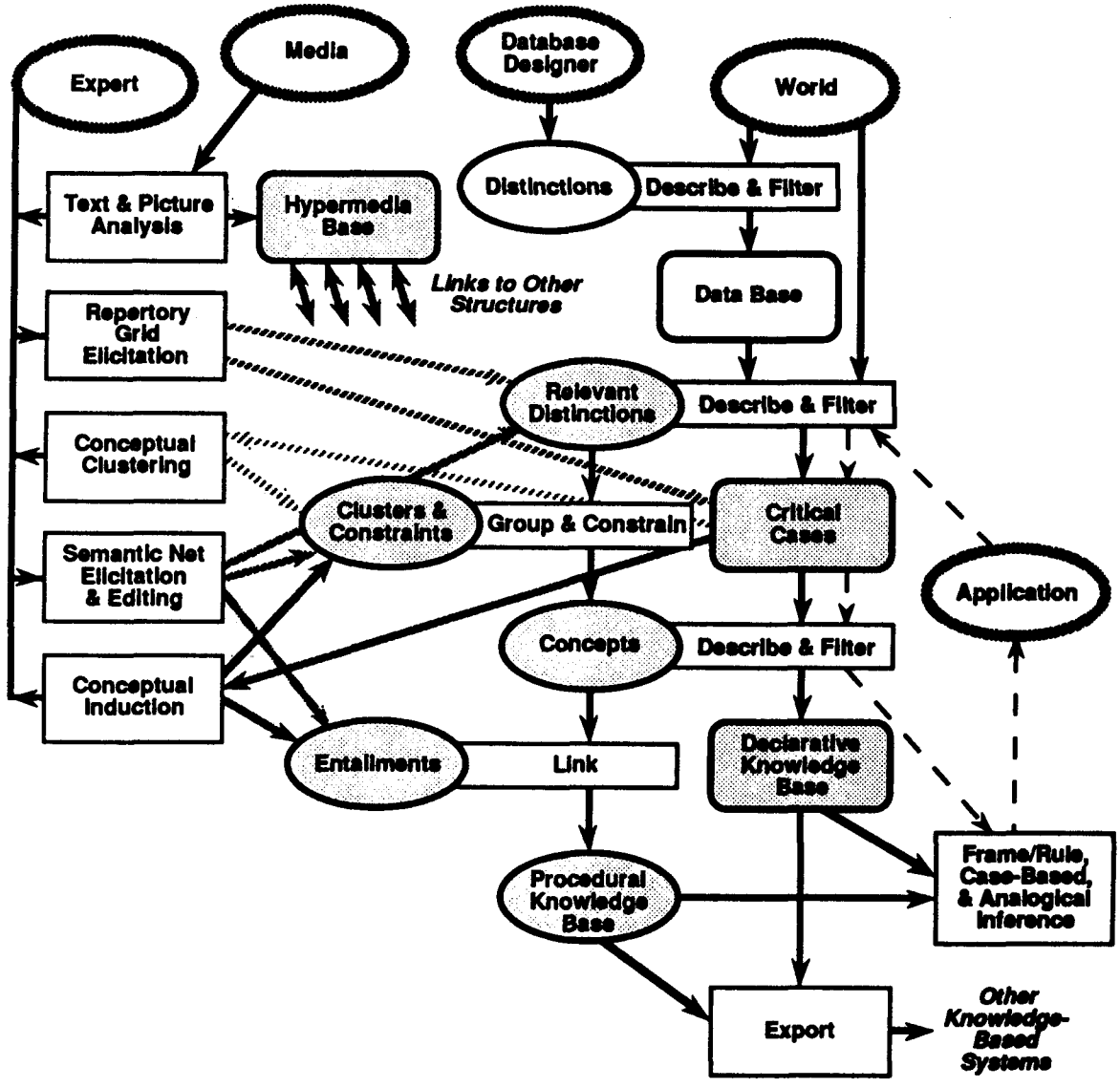

Fig.8 Integrated knowledge acquisition system architecture

The architecture of Figure 7 is intended to be illustrative of the way the various knowledge acquisition techniques described naturally combine, rather than a rigid framework for an integrated tool. For example, some sub-domain structures may be developed by direct editing, others by induction from databases, others by text analysis, and others by tools not yet defined or developed. The point is that the techniques and tools that we have available now come together naturally in this framework, and it also provides an open architecture for incorporating further techniques and tools.

Figure 8 combines and extends Figures 2, 3, 4 and 5 to show the modules necessary to support the architecture of Figure 7. Nearly all the modules shown have been described already. At the upper left, text and picture entry and analysis are shown as prompting the expert and developing a hypermedia base that also has links to the computational knowledge structures.

At the lower right of Figure 8 the knowledge base has been separated into a procedural one based on the rules and a declarative one based on the cases, and two additional inference paradigms have been added. The center one combines frame/rule inference with *case-based* inference, as, for example, in PROTOS (Bareiss, 1989) The lower one provides *analogical* inference (Leishman, 1989) based on the cases in the declarative knowledge base, as, for example, in AQUINAS' performance module. These mixed paradigms based on both abstract knowledge and concrete cases are seen as the target inference modes. Even though inference is integrated, at the bottom right of Figure 8 an export module is shown since transfer of knowledge bases to specialist performance systems is still seen as an important requirement. We need to integrate performance tools with knowledge acquisition tools for testing and validation, and for long-term support and updating. However, there will continue to be major requirements for stand-alone knowledge acquisition tools and stand-alone performance tools optimized for their primary tasks.

4 CONCLUSIONS

An architecture for knowledge acquisition systems has been proposed that is based upon the integration of existing methodologies, techniques and tools developed within the knowledge acquisition, machine learning, expert systems, hypermedia and knowledge representation research communities. Existing tools have been analyzed within a common framework to show that their integration can be achieved in a natural and principled fashion. A detailed architecture for integrated knowledge acquisition systems has been proposed, much of whose implementation has been illustrated in the references given in the paper.

While the emphasis of this paper has been on the development of integrated architectures and methodologies, we hope also that the analysis of different approaches to knowledge acquisition within a common framework will be of value to those using individual tools also. Knowledge engineering and knowledge modeling are complex processes requiring major effort and the utilization of a wide variety of sources and knowledge elicitation and analysis techniques. The approaches that have been developed in the past decade are not competetive alternatives, but rather complementary methodologies and tools that need to be used together appropriately.

Our emphasis on integrated architectures should not be taken as advocacy of monolithic tools attempting to encompass all approaches. Much of our own research has been based on the heterogeneous integration of tools that were not originally designed to work together. How the required integration is achieved is an implementation decision, and raises concerns about user interface uniformity and consistency, communication protocols, and knowledge interchange formats which we have addressed elsewhere (Gaines, 1990; Gaines, Linster and Shaw, 1992; Gaines, Rappaport and Shaw, 1992).

This paper has focused on tool integration and knowledge structure integration and has not discussed knowledge level integration through the development of various kinds of generic ontologies. The knowledge level requires a paper of its own for proper treatment and is largely orthogonal to the issues discussed in this paper. For example, the KADS knowledge engineering methodology (Akkermans, van Harmelen, Schreiber & Wielinga, 1992) can be supported through the integrated architecture described, as can approaches based on role-limiting methods (McDermott, 1988) and generic tasks (Chandrasekaran, 1988). It is not necessary to tailor the tools to the methodologies provided the integrated architecture provides effective support for modular libraries of knowledge structures that can be used in the inititial stages of knowledge acquisition.

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