USING KNOWLEDGE ACQUISITION TOOLS TO SUPPORT CREATIVE PROCESSES

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Abstract: Many of the tools developed within the knowledge acquisition research community to support the knowledge engineer in developing knowledge-based systems are based on methodologies from psychology, education or management designed to support people in developing overt conceptual structures. Often the root discipline already has explicit models of the roles of these methodologies in supporting the human creative process. Given the technical progress in developing a variety of interactive knowledge acquisition tools in recent years it is appropriate to investigate the applicability of these tools to their original domains of application. This paper reports some initial experiments on the application of knowledge acquisition tools to support first year graduate students in establishing their own research directions and identities.

INTRODUCTION

Human creativity is a puzzle within an artificial intelligence and knowledge acquisition context. We expect creativity to be associated with intelligence, yet factor analyses of intelligence tests and divergent thinking tests suggest that creativity is a distinct factor of ability independent of intelligence (Bolton, 1972). Logically, the puzzle is perhaps resolved if one thinks of it in terms of the difference between the capabilities to perform a task *well*, and those to perform it both well and *differently*. Originality is not valued positively within the current performance paradigms of artificial intelligence research. On the contrary, we have been concerned with systems that mimic human expertise, and our evaluations are higher the closer the performance is to established human norms. A highly creative person would not come out well within such an evaluation framework.

However, much of what has been done within the knowledge acquisition research paradigm is potentially valuable to creativity research and to the support of human creativity. The knowledge acquisition community has developed many tools designed to elicit expertise (Boose & Gaines, 1988, 1990). These are apparently within the performance framework noted above—to 'snapshot' existing expertise. However, it has been realized that, as Clancey (1989, 1990) has stressed, while the expertise may exist, the overt knowledge that we presuppose to underlie it may not pre-exist. Skilled performance in the neural network that is the brain is not necessarily based on overt knowledge structures (Gaines, 1991b). Indeed, there is no basis other than explicit presupposition to suppose that there *are* 'knowledge structures' underlying expertise.

Given this shift in perspectives, knowledge acquisition tools may be regarded, not as transferring knowledge, but rather as supporting the expert in building a model of his or her skill sufficient to emulate it. One need not presuppose that such a model pre-exists in a form to be 'transferred.' Since the roots of most knowledge acquisition tools is in other disciplines, such as psychology, anthropology and management (Shaw & Woodward, 1990), and the original purpose was often to aid people in understanding their own psychological processes, it is plausible that the computational tools developed to support conceptual model building may serve other purposes. In particular, they may be relevant to the support of the human creative process.

SUPPORTING CREATIVITY

Barron, who has authored a number of major encyclopedia articles on creativity, recently advanced what he sees as the current consensus of the nature of creativity:

"1. Creativity is an ability to respond *adaptively* to the needs for new approaches and new products. It is essentially the ability to bring something new into existence purposefully, though the process may have unconscious, or subliminally conscious, as well as fully conscious components. Novel adaptation is seen to be in the service of increased flexibility and increased power to grow and/or to survive.

2. The "something new" is usually a *product* resulting from a *process* initiated by a *person.* There are three modes in which creativity may easily be studied: as product, as process, as person.

3. The defining properties of these new products, processes, and persons, are their originality, their aptness, their validity, their adequacy in meeting a need, and a rather subtle additional property that may be called, simply, *fitness*—esthetic fitness, ecological fitness, optimum form, being "right" as well as original at the moment. The emphasis is on whatever is fresh, novel, unusual, ingenious, clever, and apt.

4. Such creative products are quite various, of course: a novel solution to a problem in mathematics; an invention; the discovery of a new chemical process; the composition of a piece of music, or a poem, or a painting; the forming of a new philosophical or religious system; an innovation in law; a fresh way of thinking about social problems; a breakthrough in ways of treating or preventing a disease; the devizing of new ways of controlling the minds of others; the invention of mighty new armaments, both of offense and defense; new ways of taxing the citizens of a country by its government; or simply a change in manners for multitudes of people in a specific period of time." (Barron, 1988)

There is *prima facie* validity of knowledge modeling tools as support for the creative process if one examines the literature on scientific development, change and revolution. For example, Torretti, in analyzing the development of modern physics, considers the dynamics of conceptual schema to be the basic framework within which all other activities can be located. In particular, he analyzes in detail the essential limits to conceptual innovation that provide continuity in scientific development, noting that:

"C1. Some concepts are immune to change, and they provide a stable reference to decisive facts.

C2. The new concepts are arrived at through internal criticism of the old, by virtue of which the facts purportedly referred to by the earlier mode of thought are effectively dissolved.

C3. Reference to facts does not depend on the concepts by which they are grasped." (Torretti, 1990)

Tools that provide means to make these relations between concepts more overt and operational should have a role in the creative process of conceptual transformation.

Barron, Torretti, and many others, describe the phenomena of creativity, but what are its underlying psychological processes? One of the first psychologists to consider the relationship between the convergent and divergent knowledge processes of creativity within a cognitive framework was George Kelly (1955) whose *personal construct theory* presents a person as exploring his or her environment, collecting data about the world and constructing a personal reality from which to view it. The repertory grid methodology used in many knowledge acquisition tools (Shaw & Gaines, 1983, 1987; Boose, 1984; Boose & Bradshaw, 1987; Diederich, Ruhmann & May, 1987) stems from this perspective, and supports the elicitation and analysis of the construct system, or conceptual framework, with which an individual operates in his or her own domain.

Kelly analyzes the dynamics of change in a person's construct system in terms of a *creativity cycle* in which convergent and divergent thinking alternate. A system of personal constructs is not fixed, but may vary from one occasion to another:

> There are typical shifts in the sequence of construction which people employ in order to meet everyday situations....The Creativity Cycle has to do with the way in which a person develops new ideas. (Kelly, 1955, pp.514-515).

Kelly sees convergence/divergence as a sequence of loosening and tightening of constructions. A person who uses only tight construing may be very productive but cannot be original. On the other hand, loose construing is characterized by a person's "preposterous thinking" (p. 529) which is unformulated and often preverbal. The structured alternation of these processes is what we perceive as the creativity underlying intelligent behavior. Thus the paradoxical relation expressed at the start of this section is explained in terms of sequentiality—the full scope of intelligence involves not only a high level of performance but the adaptive renewal of the underlying basis of that performance through a process of creative reconstruction.

Figure 1 illustrates the nature of the creativity cycle and the types of process involved in it, together with the roles that we have designed the associated computer-based tools to play in supporting these processes. Note that we see that phase of the cycle that is divergent and deconstructive as equal in importance to that which is convergent and constructive. It is as important to be able to deconstruct a well-established base of received knowledge through critical processes that can start a new creativity cycle, as it is to be able to clarify and formalize ideas into theories. This is particularly so for new graduate students where the weight of received wisdom is often the most significant burden impeding their establishing their own research directions and identities. Creativity is truly a cyclic process—one of going contrary to one's current preconceptions—but each phase of the cycle is different in nature and requires its own support. At one time one may be clarifying and substantiating one's preconceptions, at another attempting to identify and demolish them.

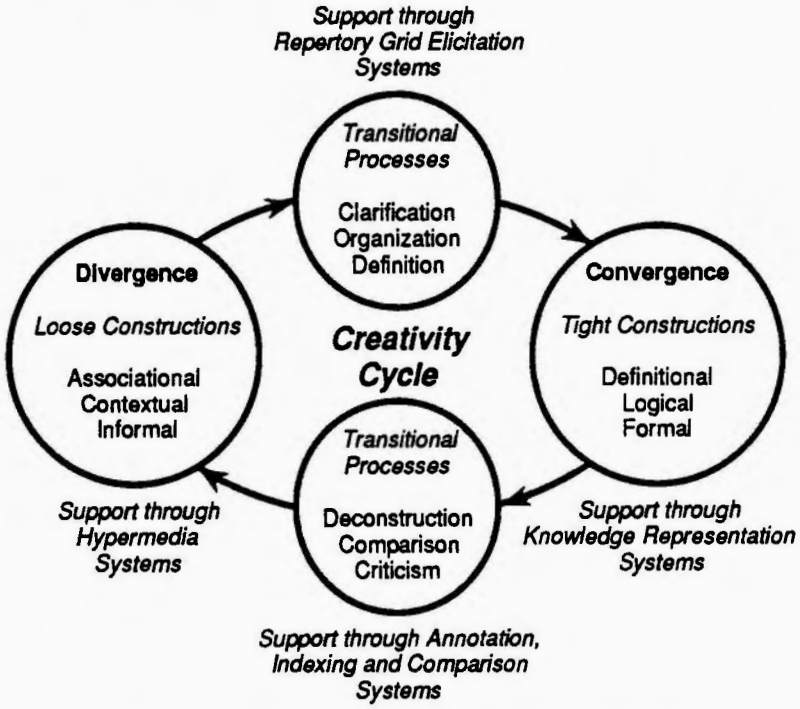

Figure 1 Creativity cycle and its support

We are studying the application of knowledge acquisition tools as systems to support the creative component of scientific knowledge processes. This paper presents Kelly's personal construct theory and, in particular, the repertory grid, as a method of eliciting relevant but abstract constructs about the topic, together with semantic nets which are used to produce a concept map

of the cognitive structures involved. Hypermedia is used for annotation and explanation, to add notes, diagrams and links to other material during the creativity process. An empirical study has been undertaken of the system in use by ten graduate students in a Cognitive Science course in a university department of Computer Science to explore and elaborate aspects of their research topics. Some initial results are presented.

KNOWLEDGE ACQUISITION TOOLS

There are well over one hundred knowledge acquisition tools named and described in the current literature (Boose, 1989). However, a recent classification of tool architectures has characterized them in terms of four major types (Gaines, 1990):

- Semi-formal elicitation and structuring through hypertext and hypermedia—used to capture raw knowledge at the pre-computational stage—the tool typically being based on a hypermedia system such as Apple's HyperCard.
- Direct editing of knowledge in a semantic network, frame, rule, representation—used with overt, computational knowledge structures directly available from an expert or derived through other tools—the tool typically being some form of graphic knowledge editor for semantic nets.
- Indirect elicitation through critical cases described in relevant attributes—used when the expert cannot provide overt knowledge structures but can provide high quality stereotypical case data—the tool typically being graphic interaction through a repertory grid methodology.
- Inductive derivation of knowledge from data sets of varying quality—used when the expert cannot provide high quality case data but can give access to substantial databases of lower quality data—the tool typically being a derivative of ID3 or AQ11.

All of these types of tools seemed to us to have some *prima facie* validity as potential support for the creative process. Our logic was that tools designed to help an expert make his or her knowledge structures overt could also support students in developing models of their own intuitions. Such tools might counterbalance the weight of existing received knowledge, particularly used by first year postgraduate students attempting to establish their own research directions and personal research identities. The significance of the knowledge acquisition tools and underlying methodologies is threefold: they are *reflective*, reflecting back to the student his or her own vocabulary, nascent knowledge structures, and their implications; they are *adaptive*, capable of being continually edited and refined with little ergonomic cost; they are *operational*, generating knowledge structures capable of being used in the computer for reasoning, simulation and problem-solving.

The support of students' learning process, in particular their personal creativity, has been a major application envisioned for hypermedia systems since their inception (Landow, 1989). The capability to access, develop and organize multiple sources and forms of knowledge is at the heart of academic scholarship. The capability to create, explore and evaluate patterns of knowledge through linking diverse materials supports the formation of the *insights* that Lonergan (1958) argued were the essence of the scientific process (Compton & Jansen, 1990). However, while the representational and linkage structures of hypermedia can support many of the argument forms significant to human discourse, they stop short of supporting the operationalization of knowledge in a logical, computable form. That, so far, has been the domain of artificial intelligence where formal knowledge representation schema support inferential reasoning processes within the computer.

However, as noted by Travers (1989), there are close relations between knowledge structures represented through hypertext webs and through semantic networks. The informal, creative richness of hypermedia and the formal, scientific precision of logic programs are not poles apart. Perhaps the human creative process of bridging between open textured ideas and closely defined theories can be supported by a technology bridging between hypermedia and semantic networks. That is the motivation underlying the system development and experiments reported in this paper.

In the early 1980's we reported the application of computer-based repertory grid tools as computer-assisted learning (CAL) tools to track the creativity cycle in a student's learning progression (Shaw & Gaines, 1982). We had already suggested that such tools could be used to derive the conceptual models underlying expertise in developing expert systems (Gaines & Shaw, 1980), and demonstrated their role in eliciting accounting expertise at an early expert systems conference (Shaw & Gaines, 1983). Boose (1984) presented parallel research in an industrial context at AAAI'84, and repertory grid methodologies and tools have since become routine items in the knowledge engineer's toolkit. In particular they have been greatly extended in both the richness of knowledge representation and the quality of interactive computer support and online computer analysis and its graphic presentation.

It has seemed to us as we enter the 1990's that the wheel has come a full circle and that it is time to test the tools developed for specialist expert system development as general *knowledge support systems* with applications to creative thinking at all stages of the educational, scientific and artistic process. We have at our disposal the original repertory grid tools, now greatly enhanced and integrated with hypermedia systems and a range of expert system shells (Gaines, Rappaport & Shaw, 1989; Gaines & Linster, 1990). We also have a graphic knowledge editor designed on the one hand for ease of use through simple MacDraw-like editing features, but on the other hand implementing a well-defined visual conceptual language supporting both Kelly's construct hierarchies and Brachman's KL-ONE conceptual structures (Gaines & Shaw, 1990). In the context of this paper, it is particularly interesting to note the way in which the graphic knowledge editor is able to support the concept maps already used within the educational system to help students elucidate and communicate their ideas (Novak & Gowin 1984; Lambiotte, Dansereau, Cross & Reynolds, 1989).

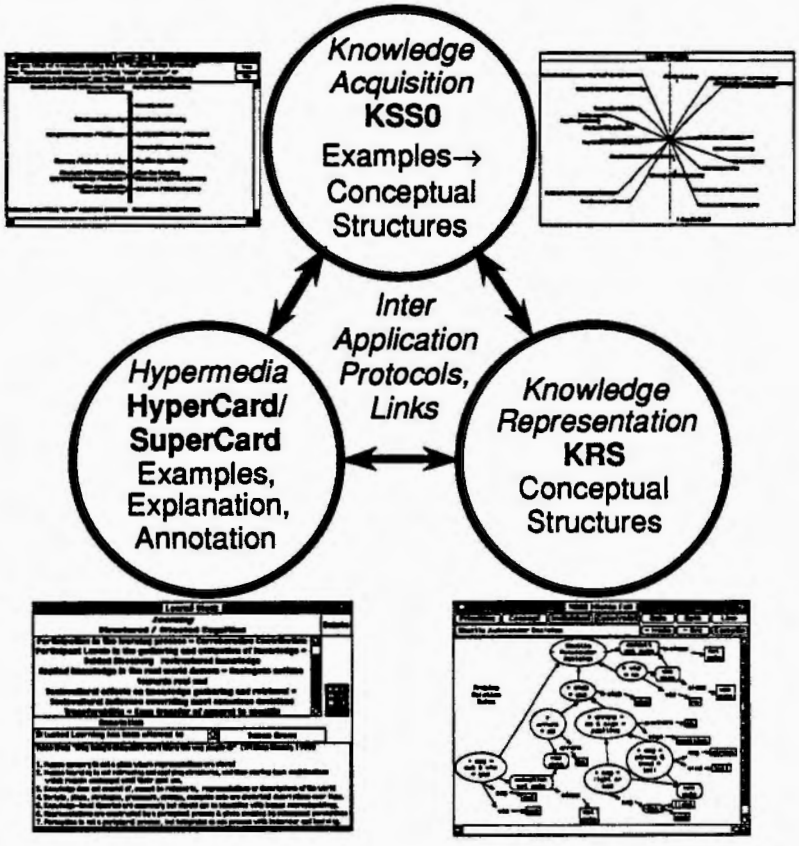

Figure 2 Integrated hypermedia, knowledge acquisition and knowledge representation

Figure 2 shows the way in which the hypermedia, knowledge acquisition and knowledge representation tools are integrated to provide an environment supporting students' creativity. The three tools communicate through inter-application protocols enabling one program to respond to the selection of actions in another. For example, examples entered in KSS0 have associated popup menus, one option of which is to transfer to an annotation card automatically created in HyperCard or SuperCard. Conversely, the grid associated with a HyperCard stack or SuperCard project can be loaded into KSS0 and clustered using commands entered through buttons in the stack or project. Similar links integrate the other applications.

The remainder of this paper gives an overview of each of the tools, illustrates their application in the hands of a graduate student, and summarizes our preliminary experience with ten students experimenting in their use.

THE HYPERTEXT TOOL

The hypermedia component of the system is the most open-architecture since both HyperCard and SuperCard provide complete programming languages and the capability to identify new user interfaces very simply and naturally. Students were encouraged to use this openness to develop interactive note books for their projects, and did so extensively, typically developing a framework for their studies and keeping logs of ideas and graphical outputs resulting from use of the other tools. One student submitted his final project as a stack with links to figures, diagrams and results as illustrated in Figure 3.

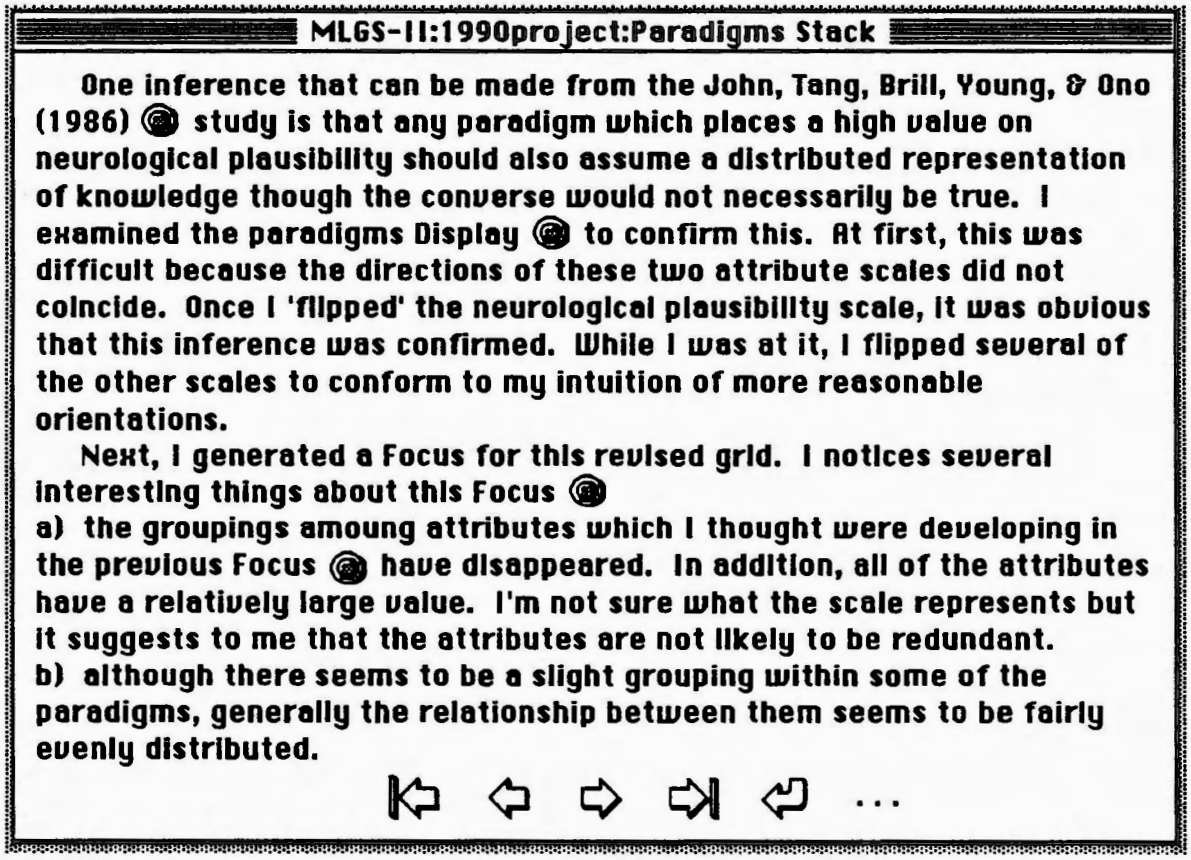

Figure 3 Card from stack submitted as final "essay" assignment

However, a completely empty stack with no initial structure is daunting, and the KSS0 tool in particular is designed to help people elicit ideas initially. Hence, students were provided with a skeleton HyperCard stack and SuperCard project that supported inter-application communication with KSS0 and KRS. When this is running at the same time as KSS0 a popup menu cursor appears as one mouses over element names and construct pole names in graphic screens such as those of Figures 5 through 9. Mousing down when this cursor appears brings up a popup menu that offers a link to the hypertext tool. Selecting this transfers to the stack or project at the card corresponding to the element or construct, creating such a card if it does not already exist.

The upper part of such annotation cards is predefined as shown in Figure 4 to show the grid name, element or construct names, and possible construct values or actual element values. The lower part contains a scrolling text area to the left for annotation and an open area to the right for buttons linking to further annotation. Facilities for linking to subject matter video disks are also provided. All the students made heavy used of the hypermedia annotation facilities to annotate their elements and constructs and to add additional material such as references, background notes and diagrams.

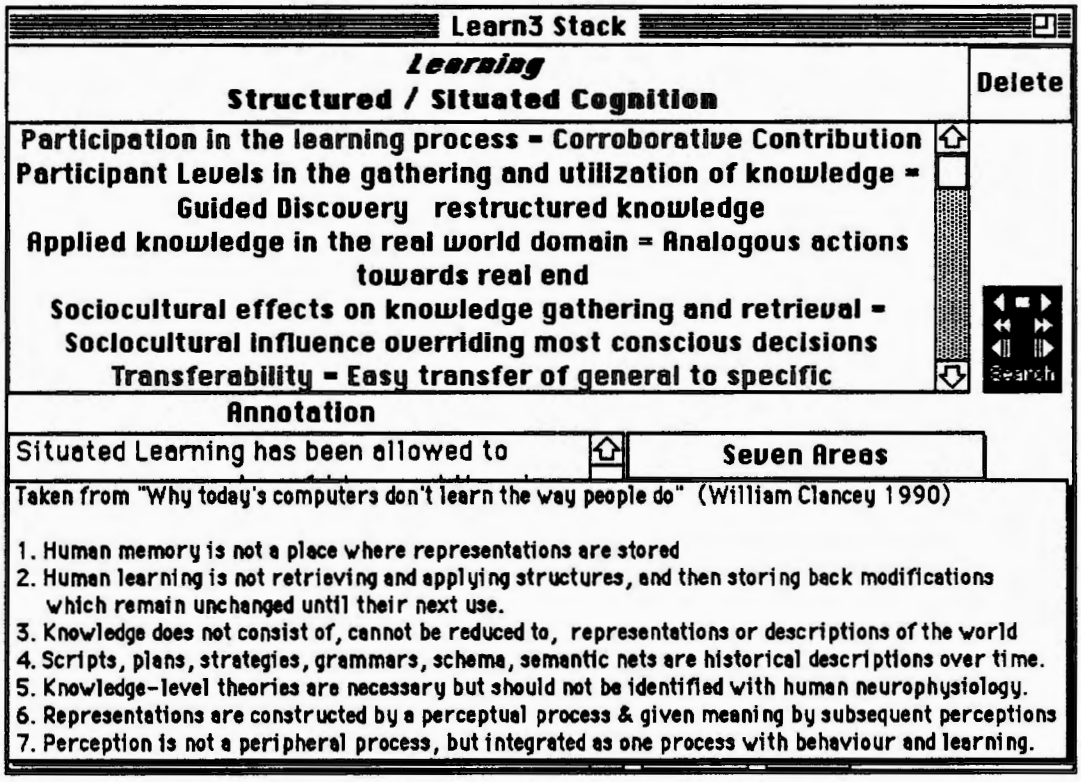

Figure 4 Element annotation card with additional annotation showing

THE KNOWLEDGE ACQUISITION TOOL

KSS0 is a knowledge support system providing an integrated set of tools for elicitation and analysis of elements and constructs in a given domain. It combines a number of different techniques, including element and construct elicitation and clustering, and is linked to an inductive rule generation program. It runs on the Apple Macintosh family of computers to provide a highly interactive and graphic knowledge acquisition environment. At the heart of KSS0 is an object-oriented knowledge base in which knowledge is formally represented as a multiple-inheritance digraph of classes, objects and properties.

The main tools in KSS0 are:

- *Elicit* accepts specifications of elements within a domain and provides an interactive graphical elicitation environment within which a person can distinguish elements to derive his or her constructs within the domain. The resultant conceptual system is continuously analyzed to provide feedback prompting the person to enter further elements and constructs.
- *Exchange* extends this to share elements and constructs between people and allows the terms in the conceptual system derived from one person to be used by another in order to determine whether the two conceptual systems are different in any way. It can also be used by the same person looking at changes in their own conceptual structures over time, for example, after reading a specific book, or exploring a particular domain.
- *Process* gives access to clustering tools for the analysis and display of the conceptual systems elicited: FOCUS shows the system as a hierarchical structure; and PrinCom as a spatial map.
- *Socio* processes results from several people to reveal the similarities and differences in their conceptual systems, or the same person at different times, construing a domain defined through common elements or constructs. It can be used to focus discussion between people on those differences between them which require resolution, enabling them to classify them in terms of differing terminologies, levels of abstraction, disagreements, misunderstandings, and so on (Shaw & Gaines, 1989).

KSS0 exports the grid data as class definitions, properties, constraints, entailments and instances to a variety of object-oriented knowledge-based system shells.

The ten graduate students were given access to KSS0 and associated tools for some two months with the assignment of developing their research ideas for their MSc research. Figures 5 through 9 give examples of the interactive graphical elicitation of constructs using KSS0 by a graduate student organizing her framework of learning strategies as exemplified by some of the publications from the Institute for Research on Learning (IRL). Figure 5 shows a construct in process of elicitation, with the elements listed on the left and being dragged on to the dimension of the bipolar construct *Facilitates Learning and Expanded Knowledge — Knowledge and Learning Hindered.*

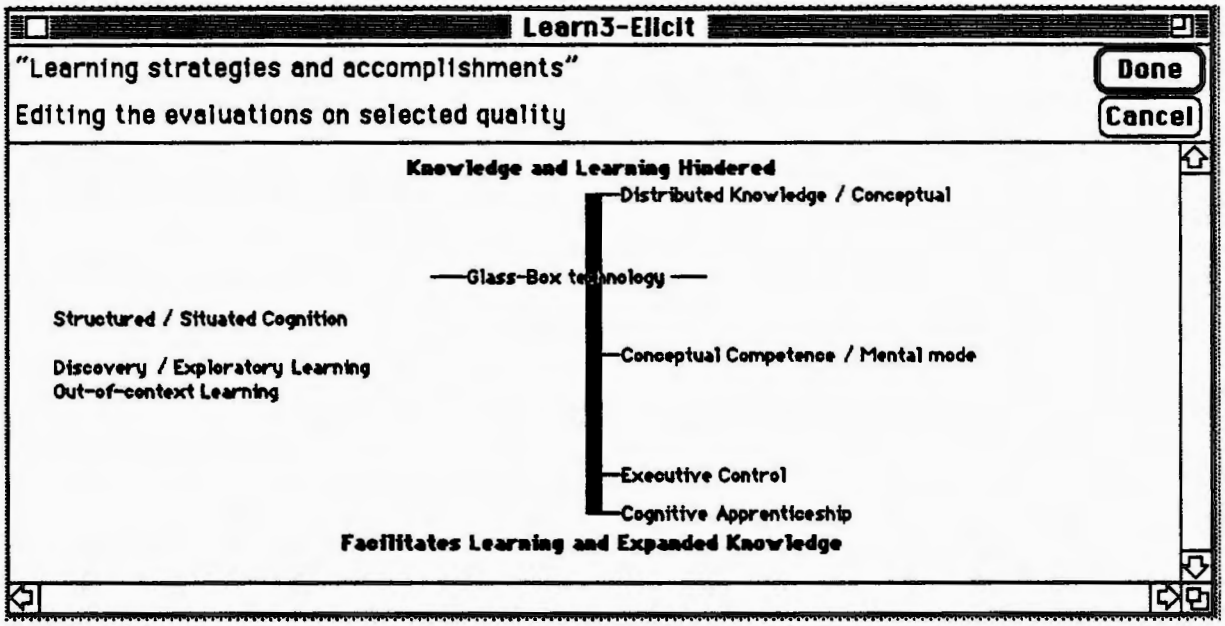

Figure 5 Construct rating during elicitation in KSS0

Figure 6 shows two constructs which are highly matched, showing the placing of the elements on each, and inviting the student to think of a new element which would reduce the match level. The popup menu is also shown, allowing the student to examine the annotation in HyperCard associated with a particular element.

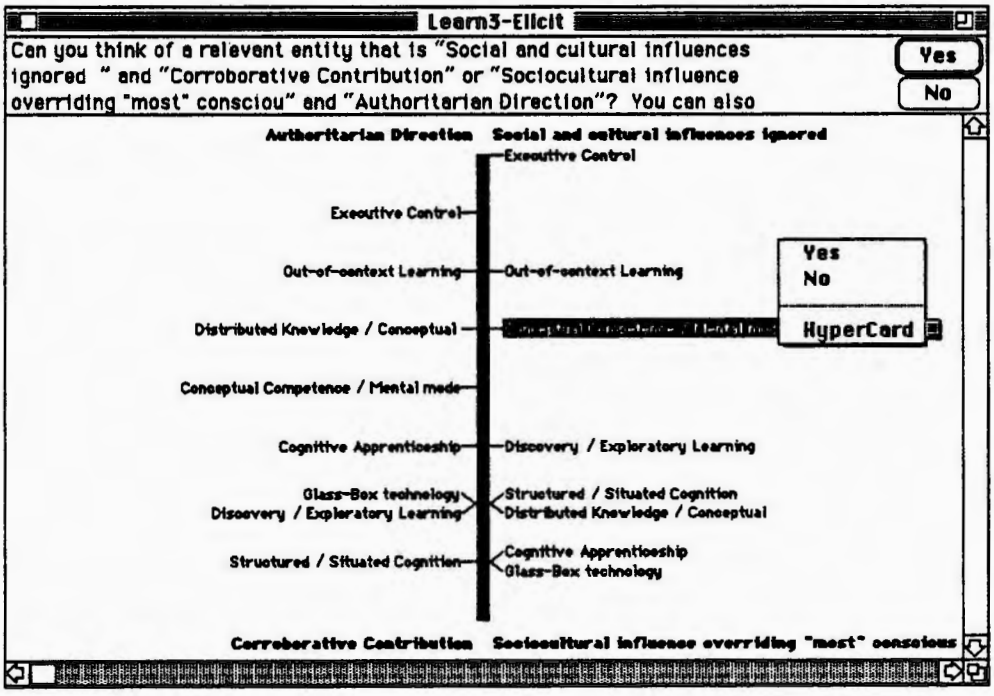

Figure 6 Construct match prompting element elicitation

Figure 7 shows a similar situation with two elements which are highly matched. The marker sticking up refers to the element *Cognitive Apprenticeship* and the marker sticking down to the other element *Structured / Situated Cognition.* Element and construct names and ratings changed at any time.

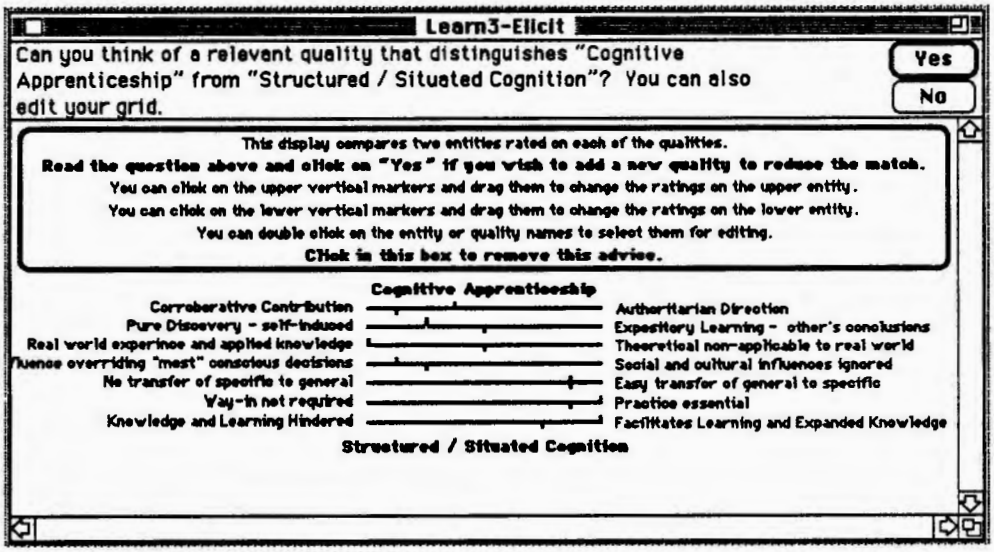

Figure 7 Element match prompting construct elicitation

KSS0 provides facilities for analyzing grids in various ways, clustering them, comparing them, deriving rules, and so on. Figure 8 shows the grid analyzed by FOCUS with the clusters on the right, and the values shaded in groups for easier interpretation, and Figure 9 shows the principal components analysis of the same data. The actual data values are also available, such as the match values and the factor loadings. The popup menu allowing access to the annotation is available for each element and construct as illustrated in Figure 9.

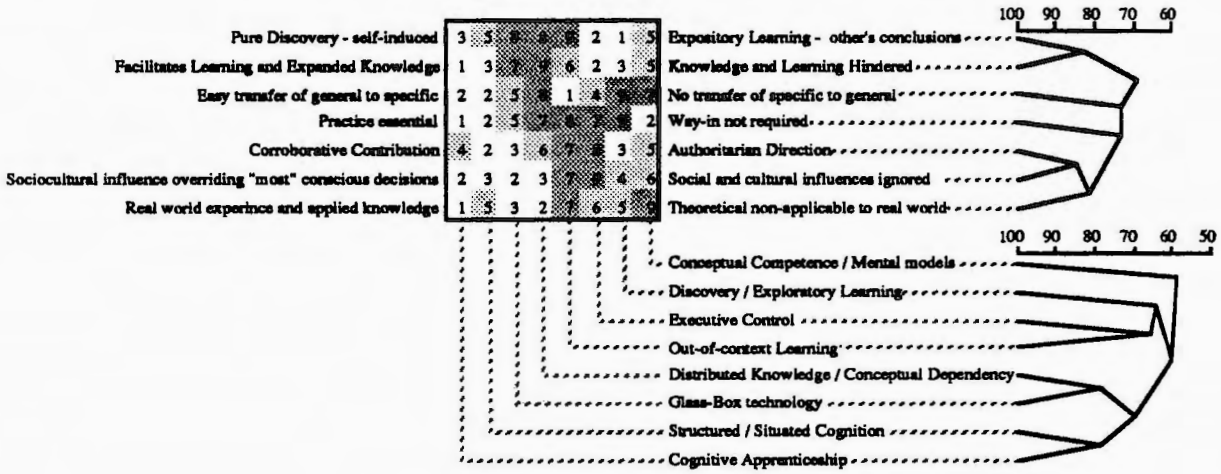

Figure 8 FOCUS hierarchical cluster analysis

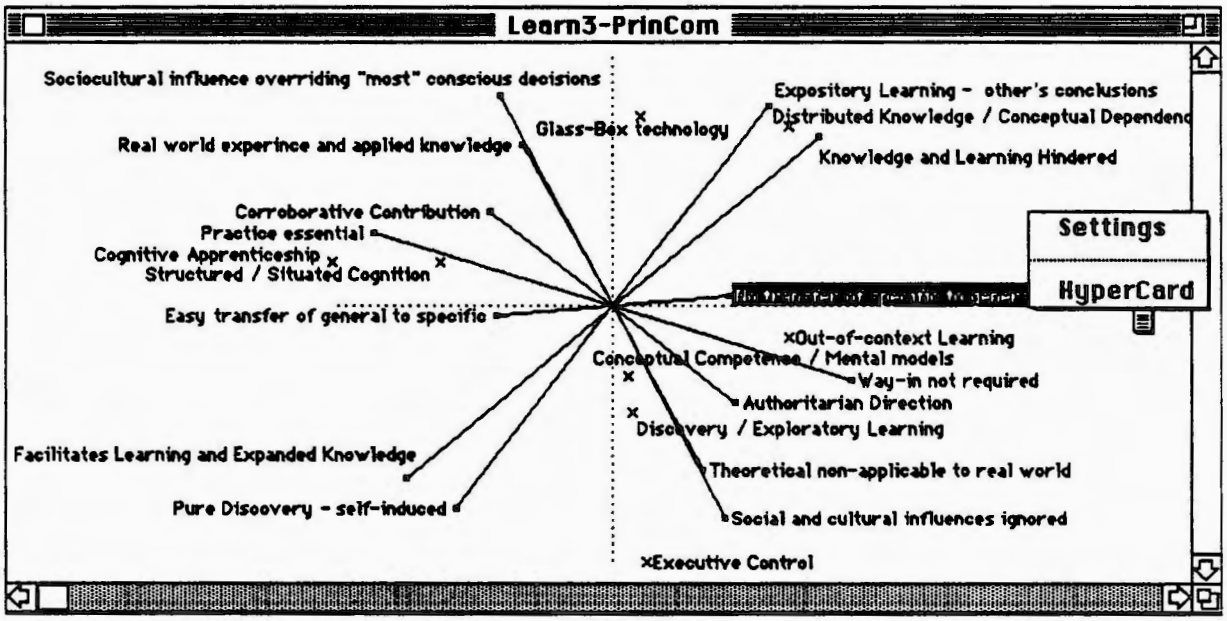

Figure 9 PrinCom spatial cluster analysis

Using the example described above the single output variable was used *Towards a Perfect System*, that is, the construct *Facilitates Learning and Expanded Knowledge — Knowledge and Learning Hindered* with the middle point described as *Limited Knowledge and Learning Gain.* Some of the rules produced by the induction system (Gaines, 1989) were:

- Knowledge is hindered when there is limited master teaching
- Knowledge is hindered when there is both cooperative participation and expository learning

- Limited knowledge gain occurs in purely theoretical environments
- Pure discovery facilitates knowledge gain
- Analogous learning supported by applied practice facilitates learning

The knowledge structures and rules developed in KSS0 may be exported as classes, objects and rules to a number of knowledge-based system shells to become overt, operational knowledge structures. This was not done in the present study, largely through lack of time and the complexity of adding yet another tool to the set that the students were involved in using. However, the creation of an operational knowledge structure may be seen as a crucial test of the convergence of ideas to a simulable form where the consequences of assertions may be inferred and tested, and the would be a useful component of future studies.

KSS0 allows grids and annotation developed by multiple users to be compared (Shaw & Gaines, 1989). One of the students asked his supervisor to create a grid using the elements and constructs from his own grid on instructible systems. Figure 10 shows a comparison of these two grid. The elements and constructs on which they agree and differ are immediately apparent and can form the focus of productive discussion; the darker shaded areas toward the bottom left showing the most conflict. Students may compare their views among themselves and with faculty. The basis of differing opinions is clearly apparent and open to discussion.

For example, the student and supervisor were in consensus on the top six constructs but had a significant conflict in their use of the bottom three constructs. Similarly, they agreed about the four top elements but had very different perspectives on the bottom one. It is valuable to focus on the conflicts and disagreements and determine their sources since differing uses of the same terminology, or different viewpoints on the same systems, may lead to misunderstanding based on tacit presuppositions.

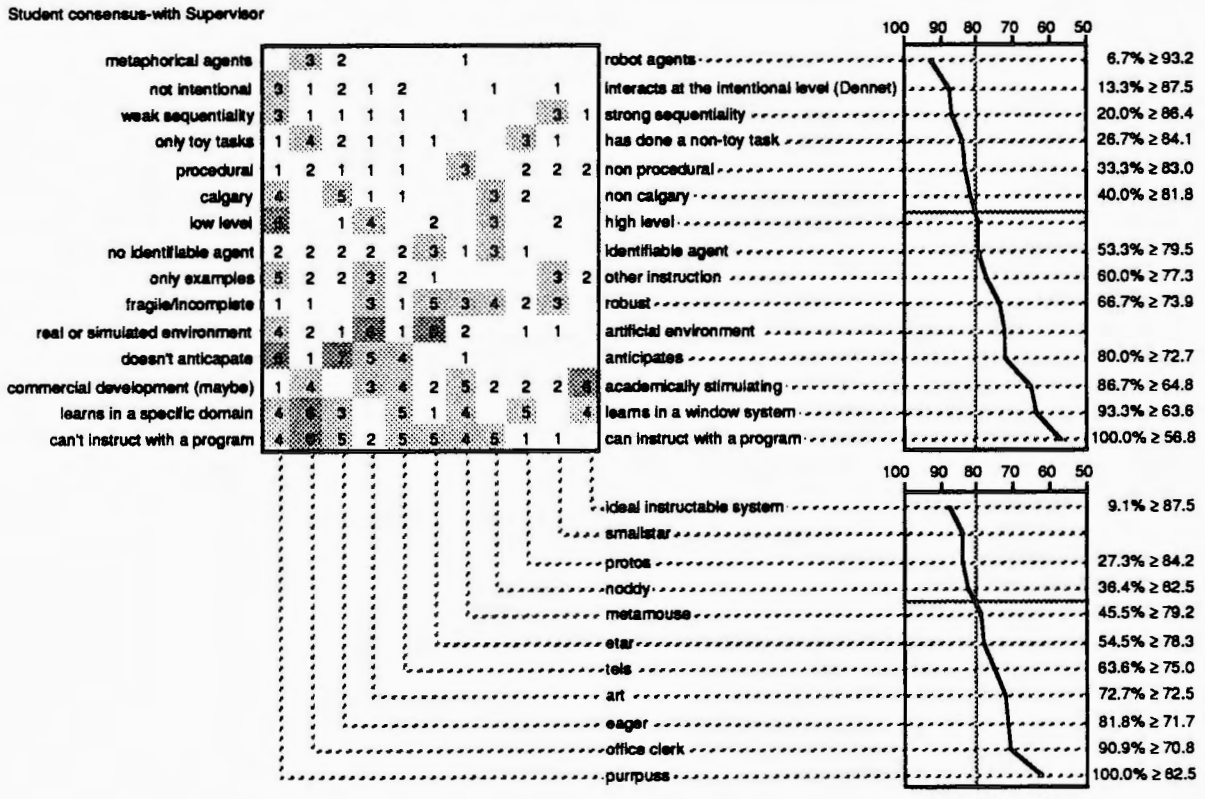

Figure 10 Comparing exchanged grids from student and supervisor

THE KNOWLEDGE EDITING TOOL

The knowledge structures developed in KSS0 can be exported to a variety of knowledge-based system shells as class, property, constraint, object, value and rule definitions. In particular they may be exported to the graphic editing tool associated with our knowledge representation server, KRS (Gaines, 1991a). Figure 11 shows the grid concepts and rules shown above exported to KRS and graphed as a semantic net.

Term subsumption, or KL-ONE-style, knowledge structures are notoriously difficult to edit because they are require the 'top-down' definition of general concepts and their stepwise refinement to more specific concepts. The grid methodology is a way of developing them 'bottom up' from cases. The KRS graphic knowledge editing tool further supports this approach (Gaines, 1991c). Knowledge structures can be developed and edited using drawing tools providing a natural visual language. The structures can extend across multiple screens supporting modularity and libraries. Structures can be freely duplicated and definitions may be fragmented across screens. The consistency of the definitions is determined only when they are compiled into a formal knowledge structure and inconsistencies are graphically highlighted.

The grapher is highly interactive. Objects, and groups of objects, may be dragged to new locations and the lines remain connected. Objects may be double-clicked to select them for editing—both text and object type may be edited. Popup menus associated with each object enable the connecting lines and arrows to be entered simply.

The visual language used in Figure 11 is precisely defined. Concepts are ovals, primitive concepts are ovals with small horizontal lines inside each side, individuals rectangles, roles (and annotation) unboxed text, rules rounded-corner boxes, constraint expressions rounded-corner boxes with small horizontal lines. The interpretation of the arrows is overloaded but well-defined by the types of the objects at their head and tail. Lines without arrows connecting primitive concepts denote that the concepts are disjoint, and connecting roles that they are inverse. The knowledge compiler traces concepts and individuals through their outgoing arrows, builds a dependency table for concepts, highlighting circular links that it will not use, and generates concept definitions and individual assertions which are passed to the server.

All of the students exported their grid data to KRS and graphed it from various perspectives. One student, who was very much taken by the graphic editing tool in its own right, used it directly to develop a number of different classifications of material in his research area of instructible systems in artificial intelligence. Figure 12 shows some concept maps produced by this student. It is noteworthy that he used KRS more as a concept mapping tool rather than as a formal visual language for term subsumption knowledge structures expressed in a visual language. He remarked that he preferred the visual language of the graphic knowledge editor to the textual approach of an outliner.

Ausubel (1969) proposed concept maps as a tool in education for both developing students' creativity and assessing their changing conceptual structures during the learning process. Novak & Gowin (1984) and Lambiotte, Dansereau, Cross & Reynolds (1989) have reported extensive use of concept maps in the educational system. Hunter, Stahl & Novak (1990) have developed CMap, a computer-based conceptual map tool. The graphic editor in KRS may be seen as a rather more elaborate and formally based version of such a tool, and it would be interesting to see its impact in use by those in the educational system already using concept maps.

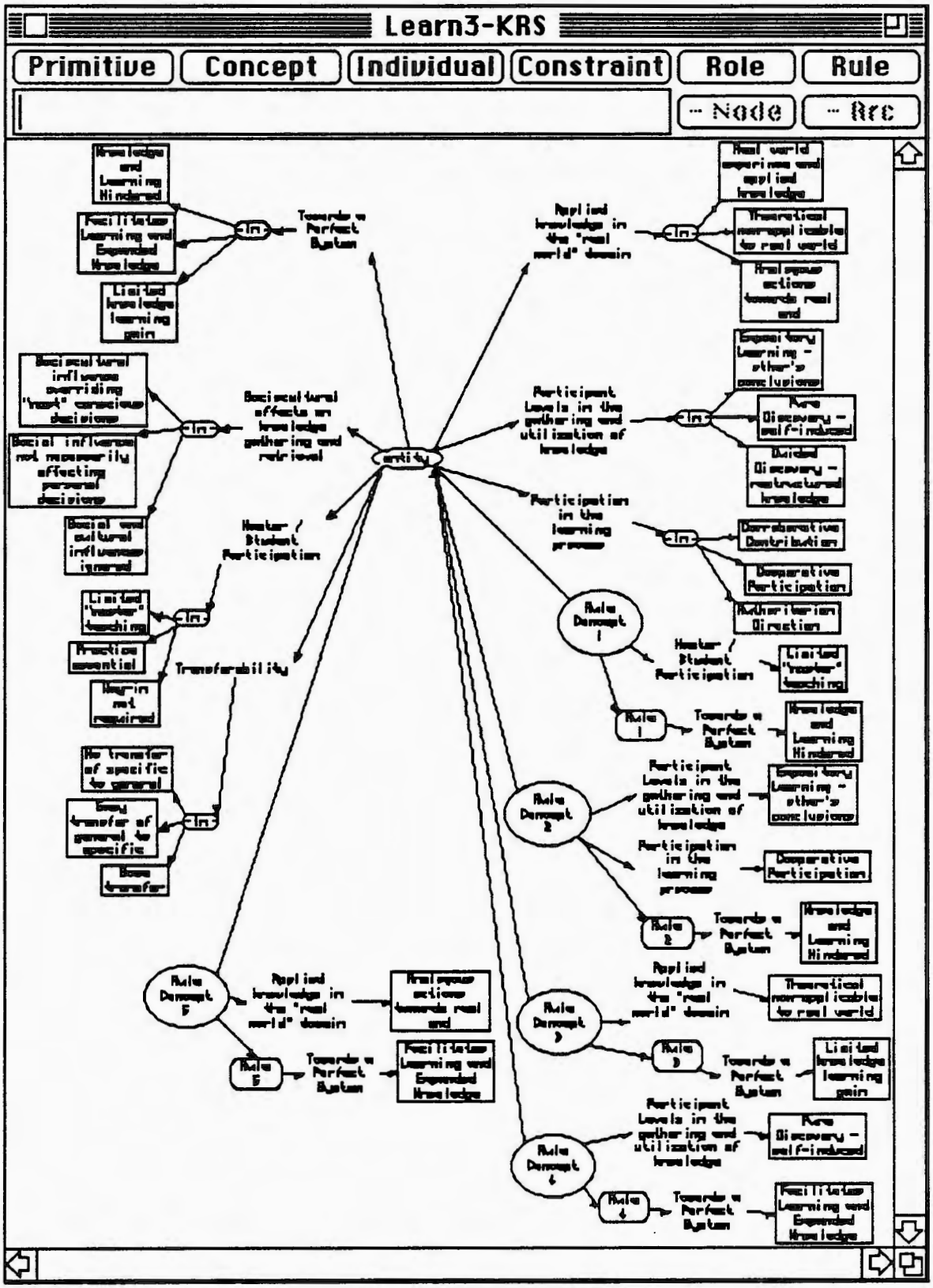

Figure 11 Grid and induced rules exported to the KRS graphic knowledge editor

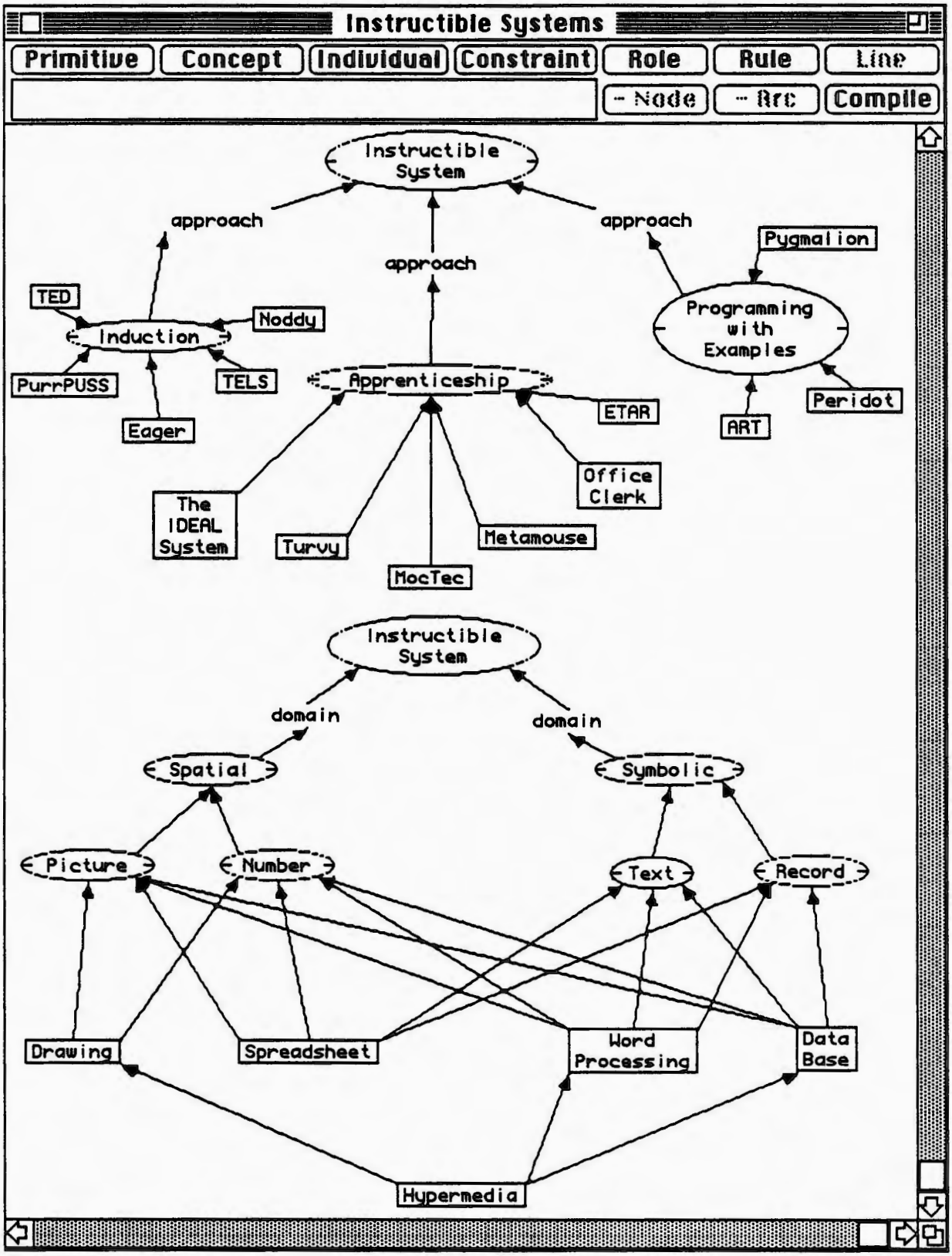

Figure 12 Concept maps produced by student researching instructible systems

SOME RESULTS

The students in the Cognitive Science course were encouraged to choose a topic which was closely related to their area of interest and their research project. We have already seen one example in the general area of situated cognition, and another in instructible systems; others included theories of mind, psychological paradigms and induction systems. Figure 13 summarizes the research topics, domain chosen for elicitation, outcome in terms of material produced, and major comments of the students on the course.

	Research Topic	Chosen Domain	Outcome	Student Comments
1	open	learning strategies	grid, knowledge structure, stack	
2	open	situated cognition	grid, knowledge structure, stack	
3	instructible systems	instructible systems	2 grids, exchange with Socio analysis, 7 knowledge structures, stacks	prefer KRS to an outliner for developing ideas
4	expository writing support tools	psychological paradigms	2 grids, knowledge structures, stack	presented results as a HyperCard stack
5	cognitive science	theories of mind	grid, knowledge structure, stack	would like to use this for my thesis
6	intelligent tutoring	Pascal statements	grid, stack	
7	open	computational learning	grid, knowledge structure, stack	
8	genetic algorithms	computer games	grid, knowledge structure, stack	
9	machine learning	induction systems	grid, knowledge structure, stack	learned a lot more about induction systems doing this sort of structuring
10	complexity of computation	fast food	grid, knowledge structure, stack	concepts in research field are already defined and not suitable

Figure 13 Summary of student experience

It can be seen that not all the students chose topics associated with their research, and it is suspected from more detailed discussion that this was a form of cognitive defense in the same way that avoidance of a primary topic is in a clinical context. There was no pressure to conform since, from an educational point of view, we were primarily concerned to introduce the students to tools within a cognitive science framework that modeled conceptual structures. The fact that they could be used for a variety of practical purposes within the lifeworlds of the students was incidental. The tools continue to be available in the Department and it will be interesting to see whether they are further used by the students concerned in the future development of their research topics.

CONCLUSIONS

What has been reported here is very much a preliminary, informal investigation of the application of tools developed within the knowledge acquisition community to support the creative process in education. Although the underlying methodologies go back many years, it is only in very recently that these tools have reached a level of usability, and deliverability on personal computers, that makes it feasible to introduce them into the educational system. There is still much to be done in the total 'packaging' of such tools for the non-AI community.

It would be very interesting as knowledge acquisition tools mature to attempt to make them available as 'conceptualization' support to the scientific community. Even though from the knowledge acquisition community perspective we still have far to go in developing theories,

methodologies and tools, and anything we have today has a poor resemblance to our aspirations, it may not be too early to investigate potential applications in the sciences. One sees many examples of scientific thinking where existing tools would help clarify the arguments.

For example, the economist Weintraub, has recently published a methodological analysis of the way in which economic knowledge is constructed and used this to study the historical development of general equilibrium theory. One of his major conclusions is:

> "The main argument that develops from this set of observations is that the literature on dynamic stability, as it developed from the 1930s to the 1950s, was formed and guided by a set of 'oppositions,' and those oppositions themselves created the language and conceptual framework that structure how modern theorists think about the economy and the way we model-construct the economy." (Weintraub, 1991)

He develops these oppositions in detail, and exhibits them and their interplay in the course of economic history. It seems likely that this research, and its presentation, would benefit immediately from the use of a repertory grid tool to analyze economic phenomena and research in terms of these oppositions.

Such types of analysis are found in many disciplines. In musicology, for example, Cogan (1984) develops a detailed analysis of the tone qualities of musical sound in terms of a set of some thirteen binary oppositions. He characterizes the changing tone structure of a number of pieces of music as they develop chronologically, and uses this to compare pieces. However, the analysis is descriptive and makes no further use of the material available which again fits neatly into a repertory grid framework.

Cruse's (1986) book on linguistic semantics provides many examples where a knowledge modeling tool could be effective in exemplifying and strengthening the arguments. For example, he argues that *father* and *mother* are "weaker opposites" than *man* and *woman* which, in turn, "are weaker than" *male* and *female*. However, the argument is highly discursive and nether logical nor quantitative. If we graph the knowledge structures involved as shown in Figure 14, it can be seen that, for example, *father* and *mother* inherit the disjoint relation between *male* and *female*, but also inherit in common the attributes of *person* and *parent*. Thus, Cruse's analysis of the relative degree of opposition in terms of commonality is apparent in this representation.

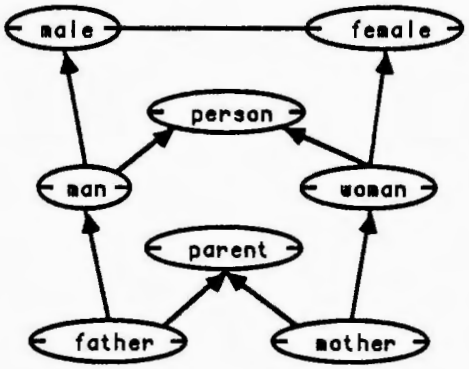

Figure 14 The relative strength of opposition apparent in a knowledge structure

Feldman, Compton and Smythe (1989) gave an example of the application of a knowledge-based tool to hypothesis testing in supporting clinical scientists developing models of a biochemical system. The tool JUSTIN was able to analyze the support or counter-indications for structural or causal hypotheses. It would be very interesting to see such tools developed more generally and made widely available in the sciences.

Thadgard has published a range of papers addressing the modeling of the phenomena of conceptual change in the sciences outlined at the beginning of this paper. For example, Thadgard and Nowak (1990) develops a very detailed analysis of the intellectual history of plate tectonics, and attempts to account for the dynamics of the early rejection and later acceptance of the modern theories. Thadgard uses a neural net model to show coherence of theories through spreading activation. This seems to give meaningful global assessments of the relative attractiveness of competing hypotheses, but is not perspicuous in showing how change occurs at the knowledge level. It would be interesting to reconstruct his analyses using knowledge modeling tools.

In conclusion, we see the support of the human creative process and the support of experts in forming overt models of a basis for their skilled performance as closely related topics. Kelly's model of creativity puts it strongly in cognitive terms that gives formal foundations to this view. Even if this is only part of the story and there are dimensions to creativity well outside the cognitive paradigm, there seems to be enough within it to make the enterprise worthwhile.

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REFERENCES

Ausubel, D.P. & Robinson, F.G. (1969). **School Learning.** New York: Holt, Rinehart and Winston.

Barron, F. (1988). Putting creativity to work. Sternberg, R.J., Ed. **The Nature of Creativity.** pp. 76-98. Cambridge: University Press.

Bolton, N. (1972). **The Psychology of Thinking.** London: Methuen.

Boose, J.H. (1984). Personal construct theory and the transfer of human expertise. **Proceedings AAAI-84,** 27-33. California: American Association for Artificial Intelligence.

Boose, J H. (1989). A survey of knowledge acquisition techniques and tools. **Knowledge Acquisition 1** (1), 39-58 (March).

Boose, J.H. & Bradshaw, J.M. (1987). Expertise transfer and complex problems: Using AQUINAS as a knowledge acquisition workbench for knowledge-based systems. **International Journal of Man-Machine Studies, 26,** 3-28.

Boose, J.H. & Gaines, B.R., Eds. (1988). **Knowledge Acquisition Tools for Expert Systems.** London, Academic Press.

Boose, J.H. & Gaines, B.R., Eds. (1990). **The Foundations of Knowledge Acquisition.** London, Academic Press.

Clancey, W. (1989). Viewing knowledge bases as qualitative models. **IEEE Expert,** 4(2), 9-23.

Clancey, W.J. (1990). The frame of reference problem in the design of intelligent machines. In K. van Lehn & A. Newell, **Architectures for Intelligence: The Twenty-Second Carnegie Symposium on Cognition.** Hillsdale: LEA.

Cogan, R. (1984). **New Images of Musical Sound.** Cambridge, Massachusetts: Harvard University Press.

Compton, P. & Jansen, R. (1990) A philosophical basis for knowledge acquisition. **Knowledge Acquisition** 2(3).241-258.

Cruse, D.A. (1986). **Lexical Semantics.** Cambridge: University Press.

Diederich, J., Ruhmann, I. & May, M. (1987). KRITON: A knowledge acquisition tool for expert systems. **International Journal of Man-Machine Studies, 26**(1), 29-40.

Feldman, B.Z., Compton, P.J. & Smythe, G.A. (1989). Hypothesis testing: an appropriate task for knowledge-based systems. Boose, J.H. & Gaines, B.R. (Eds) **Proceedings of the Fourth AAAI Knowledge Acquisition for Knowledge-Based Systems Workshop.** pp.10-1-10-20. Banff (October).

Gaines, B.R. (1989). An Ounce of Knowledge is Worth a Ton of Data: Quantitative Studies of the Trade-Off between Expertise and Data based on Statistically Well-Founded Empirical Induction. **Proceedings of 6th International Workshop on Machine Learning,** pp.156-159. San Mateo, California: Morgan Kaufmann (June).

Gaines, B.R. (1990). An architecture for integrated knowledge acquisition systems. Boose, J.H. & Gaines, B.R. (Eds) **Proceedings of the Fifth AAAI Knowledge Acquisition for Knowledge-Based Systems Workshop.** pp.8-1-8-22. Banff (November).

Gaines, B.R. (1991a). Empirical investigation of knowledge representation servers: design issues and applications experience with KRS. **AAAI Spring Symposium: Implemented Knowledge Representation and Reasoning Systems.** pp. 87-101. Stanford (March).

Gaines, B.R. (1991b) Between neuron, culture and logic: explicating the cognitive nexus. **Proceedings of ICO'91: Cognitive Science: Tools for the Development of Organizations.** pp. 222-32. Montreal: GIRICO.

Gaines, B.R. (1991c). An interactive visual language for term subsumption visual languages. **IJCAI'91: Proceedings of the Thirteenth International Joint Conference on Artificial Intelligence.** San Mateo, California: Morgan Kaufmann.

Gaines, B.R. & Linster, M. (1990). Development of second generation knowledge acquisition systems. Wielinga, B., Boose, J.H. & Gaines, B.R., Schreiber, G., van Someren, M., Eds. **Current Trends in Knowledge Acquisition.** pp. 143-160. Amsterdam, IOS.

Gaines, B.R., Rappaport, A. & Shaw, M.L.G. (1989). A heterogeneous knowledge support system. Boose, J.H. & Gaines, B.R., Eds. **Proceedings of the Fourth AAAI Knowledge Acquisition for Knowledge-Based Systems Workshop.** pp.13-1-13-20. Banff (October).

Gaines, B.R. & Shaw, M.L.G. (1980). New directions in the analysis and interactive elicitation of personal construct systems. **International Journal of Man-Machine Studies, 13,** 81-116.

Gaines, B.R. & Shaw, M.L.G. (1990). Cognitive and logical foundations of knowledge acquisition. Boose, J.H. & Gaines, B.R. (Eds) **Proceedings of the Fifth AAAI Knowledge Acquisition for Knowledge-Based Systems Workshop.** Banff (November).

Hunter, S., Stahl, H.A. & Novak, J.D. (1990). CMap: a concept mapping elicitation tool. **Technical Report #90-006,** Department of Education, Cornell University.

Kelly, G.A. (1955). **The Psychology of Personal Constructs.** New York: Norton.

Lambiotte, J.G., Dansereau, D.F., Cross, D.R. & Reynolds, S.B. (1989). Multirelational semantic maps. **Educational Psychology Review, 1**(4), 331-367.

Landow, G.P. (1989). Hypertext in literary education, criticism and scholarship. **Computers and the Humanities, 23,** 173-198.

Lonergan, B.J.F. (1958). **Insight: A Study of Human Understanding.** New York: Harper & Row.

Novak J.D. & Gowin D.B. (1984). **Learning How To Learn.** New York: Cambridge University Press.

Shaw, M.L.G. & Gaines, B.R. (1982). Tracking the Creativity Cycle with a Microcomputer. **International Journal of Man-Machine Studies, 17**(1), 75-85 (July).

Shaw, M.L.G. & Gaines, B.R. (1983). A computer aid to knowledge engineering. **Proceedings of British Computer Society Conference on Expert Systems,** 263-271 (December). Cambridge.

Shaw, M.L.G. & Gaines, B.R. (1987). KITTEN: Knowledge Initiation & Transfer Tools for Experts & Novices. **International Journal of Man-Machine Studies, 27,** 251-280.

Shaw, M.L.G. & Gaines, B.R. (1989). A methodology for recognizing conflict, correspondence, consensus and contrast in a knowledge acquisition system. **Knowledge Acquisition 1**(4), 341-363 (December).

Shaw, M.L.G. & Woodward, J.B. (1990). Mental models in the knowledge acquisition process. **Knowledge Acquisition: An International Journal,** 179-206.

Thadgard, P. & Nowak, G. (1990). The conceptual structure of the geological revolution. Shrager, J. & Langley, P., Eds. **Computational Models of Scientific Discovery and Theory Formation.** pp. 27-65. san Mateo: Morgan Kaufmann.

Torretti, R. (1990). **Creative Understanding: Philosophical Reflections on Physics.** Chicago: University of Chicago Press.

Travers, M. (1989). A visual representation for knowledge structures. **Proceedings of HYPERTEXT'89** 147-158.

Weintraub, E.R. (1991). **Stabilizing Dynamics: Constructing Economic Knowledge.** Cambridge: University Press.