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KNOWLEDGE ACQUISITION TECHNIQUES AND TOOLS: CURRENT RESEARCH STRATEGIES AND APPROACHES

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ABSTRACT

Knowledge acquisition tools can be associated with knowledge-based application tasks and problem-solving methods. This descriptive approach provides a framework for analyzing and comparing tools and techniques, and focuses the task of building knowledge-based systems on the knowledge acquisition process. Knowledge acquisition research strategies discussed at recent Knowledge Acquisition Workshops are shown, distinguishing dimensions of knowledge acquisition tools are listed, and short descriptions of current techniques and tools are given.

Keywords: knowledge acquisition tools, knowledge acquisition, knowledge-based systems, knowledge engineering, problem-solving methods, task modeling.

1 KNOWLEDGE-BASED SYSTEM APPLICATION TASKS AND PROBLEM-SOLVING METHODS

In this section, a framework for describing problem tasks and problem-solving methods is presented.

Several incompatible taxonomies exist for categorizing knowledge-based problem-solving application tasks. One common scheme, illustrated below, divides them into *analysis* tasks and *synthesis* tasks. Analysis tasks involve identifying sets of objects based on their features. One characteristic of analysis tasks is that a complete set of solutions can be enumerated and included in the system. Synthesis (generative, or constructive) tasks require that a solution be built up from component pieces or subproblem solutions In synthesis problem tasks there are too many potential solutions to enumerate and include explicitly in the system.

Analysis and synthesis tasks can be broken down into sub-task areas. One sub-task classification is shown here:

Analysis tasks
- Classification - categorizing based on observables.
- Debugging - prescribing remedies for malfunctions.
- Diagnosis - inferring system malfunctions from observables.
- Interpretation - inferring situation descriptions from sensor data.

Synthesis tasks
- Configuration - configuring collections of objects under constraints in relatively small search spaces.
- Design - configuring collections of objects under constraints in relatively large search spaces.
- Planning - designing actions.
- Scheduling - planning with strong time and/or space constraints.

Tasks combining analysis and synthesis
- Command and control - ordering and governing overall system control.
- Instruction - diagnosing, debugging, and repairing student behavior.
- Monitoring - comparing observations to expected outcomes.
- Prediction - inferring likely consequences of given situations.
- Repair - executing plans to administer prescribed remedies.

Relationships exist between tasks and problem-solving methods. For instance, the *heuristic classification* problem-solving method has been used for many knowledge-based systems that solve analysis tasks (Clancey, 1986), and is employed in a variety of knowledge-based system development tools, or "shells" (S.1, M.1, EMYCIN, TI-PC, and so on). In heuristic classification, data is abstracted up through a problem hierarchy, problem abstractions are mapped onto solution abstractions, and solution abstractions are refined down through the solution hierarchy into specific solutions.

General methods for solving synthesis tasks are sparse; Clancey classified these methods as *heuristic construction* (1986). Usually, a specific method is developed to solve a particular task, but it is difficult to generalize the method. Some form of directed backtracking or cyclic constraint exploration is often used to explore the problem space.

2 KNOWLEDGE ACQUISITION RESEARCH STRATEGIES

Musen proposed that knowledge acquisition tools could be associated with specific tasks or specific problem-solving methods. Here we propose to classify tools with tasks *and* problem-solving methods, since most tasks seemed to be strongly linked to certain types of problem-solving methods. Consequently, certain types of domain knowledge and possibly control knowledge should be acquired to build the corresponding knowledge-based system. This idea was discussed at the First AAAI-Sponsored Knowledge Acquisition for Knowledge-Based Systems Workshop held in Banff, Canada, in November, 1986 (Gaines and Boose, 1988). Builders of interactive knowledge acquisition tools were asked to try and classify their research and the research of others in terms of these relationships. Figure 1 shows a possible mapping of such relationships at a high level in the a task classification hierarchy and a problem-solving method classification hierarchy. Lower levels in the task hierarchy would be sub-tasks (i.e., trouble shooting and symptom analysis would be found under diagnosis), and the leaves of the task hierarchy would be specific application problems to be solved.

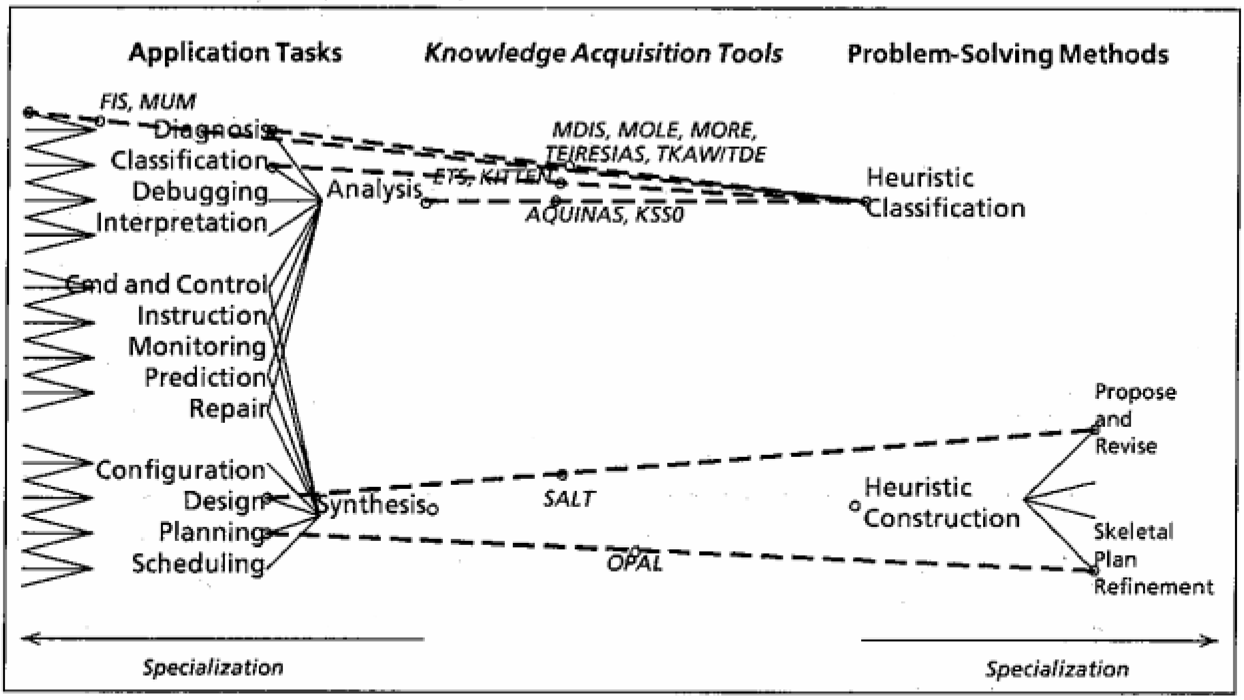


Figure 1. Knowledge acquisition tools may be associated with relationships between application tasks and problem-solving methods.

Knowledge acquisition tool research fell into several categories. Descriptions and references for the tools mentioned here are given later.

Research strategy 1:
Find and clarify knowledge acquisition techniques for a task-to-method relationship (usually a domain specific task employing a highly specialized method using much domain knowledge, or a general task employing a general method with little domain knowledge).
Examples for specific task domains ("bottom up") include OPAL, STUDENT, FIS, and MUM. Examples for general analysis tasks ("top down") include ETS, KITTEN, KRITON, AQUINAS, and KSS0.

Research strategy 2.
Pick a task, find and develop knowledge acquisition techniques for an applicable method, and then see if the method and strategies will generalize to another related task.
Examples include ("middle out") TEIRESIAS, MDIS, MOLE, MORE, INFORM, KNACK, SALT, and TKAW.

Research strategy 3.
Develop languages for defining and describing tasks and methods.
Examples include the work of Bylander and Mittal (1986), Bylander and Chandrasekaran (1987), and Gruber and Cohen (1987).

Research strategy 4.
Build intelligent editors to help AI programmers construct large knowledge bases.
Examples include CYC, KREME, and NEXPERT.

Research strategy 4 was controversial. Some argued that knowledge should be tested for specific purposes as it is acquired rather than being constructed in a "use-vacuum." Proponents of the strategy stated that future expert systems will require these large knowledge bases to avoid problems of brittleness and narrowness of scope and to be able to perform analogy and discovery, and that tools to build and manage large knowledge bases should be developed now.

3 KNOWLEDGE ACQUISITION TOOLS: DIMENSIONS, TECHNIQUES, AND DESCRIPTIONS

Four Knowledge Acquisition for Knowledge-Based Systems workshops have been held since 1986 (see the bibliography for proceedings information):

First AAAI-Sponsored Knowledge Acquisition for Knowledge-Based Systems Workshop, Banff, Canada, November, 1986.

First European Knowledge Acquisition for Knowledge-Based Systems Workshop, Reading, England, September, 1987.

Second AAAI-Sponsored Knowledge Acquisition for Knowledge-Based Systems Workshop, Banff, Canada, October, 1987.

Second European Knowledge Acquisition for Knowledge-Based Systems Workshop, Bonn, Germany, June, 1988.

The next workshop will be:

Third AAAI-Sponsored Knowledge Acquisition for Knowledge-Based Systems Workshop, Banff, Canada, November, 1988.

Representative knowledge acquisition techniques and tools presented at these workshops are described and analyzed below. First, an analysis of tools and tool dimensions is shown. Then, knowledge acquisition techniques and methods are listed and briefly described, along with computer-based tools, if any, that employ them. Finally, representative tools are listed, briefly described, and referenced.

3.1 Knowledge Acquisition Tool Dimensions

AQUINAS, a knowledge acquisition tool in use at The Boeing Company, was used prior to one of the Knowledge Acquisition Workshops to classify the tools and develop tool dimensions (references for AQUINAS appear below).

Knowledge in AQUINAS is represented, in part, in repertory grids. Objects appear along one axis of the grid and dimensions or traits appear along the other axis. AQUINAS helps the expert develop, analyze, refine, and test knowledge. A preliminary grid developed for the knowledge acquisition tools is shown in Figure 2.

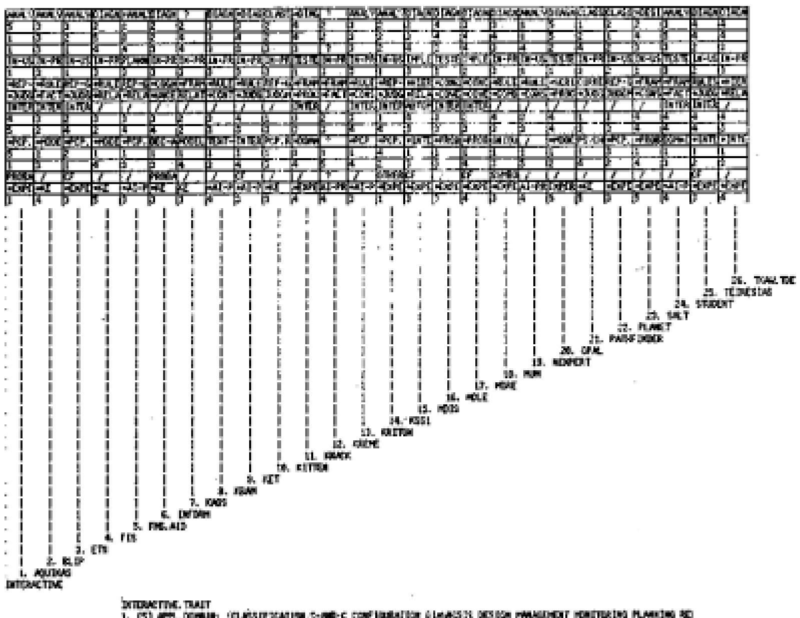


Figure 2. A preliminary repertory grid developed using AQUINAS to help analyze knowledge acquisition tools. Nominal as well as ordinal values are represented. *Distributions* of values exist when values in the grid are preceded by "*;" the highest value in the distribution is shown.

Eventually, AQUINAS elicited the following set of knowledge acquisition tool dimensions:

Application task dimensions
- Level of generality (domain dependence) - how domain-dependent is the tool?
- Analysis / synthesis - What broad categories of application tasks can the tool address?
- Specific task - Has the tool been built for a specific task? If so, what is the task?
- Application statistics (number and size of applications) - How many applications have been built with the tool? How diverse are they? How large are they? How much of the finished system did the tool help build?

Knowledge acquisition techniques and methods (these are listed separately below)

Utility dimensions
- Automated tool / semi-automated tool / manual technique - How much of the technique is implemented as a computer program? How "smart" is the tool? Is effective tool use dependent on the user, or does the tool offer semi-automated or automated assistance?
- Efficiency of use; speed of use - How hard is the tool to use? How efficient is knowledge elicitation and modeling? How well are the techniques implemented?
- Expertise representation method (cognitive maps, concepts, correlations, decision tables, frames, goal structures, hierarchies, operators, probability distributions, relations, repertory grids, rules, scripts, tables)
- High-level techniques / low-level techniques - How sophisticated are the techniques used?
- Implementation stage (planned, in progress, implemented, tested, in use, past use)
- Knowledge types (causal knowledge, classes, conceptual structures, constraints, control, covering, example cases, explanations, facts, goals, judgments, justifications, preferences, procedures, relations, spatial, strategic, temporal, terminology, uncertainties)
- Learning component (automatic, interactive, none) - If there is a learning component in the tool, how powerful is it? Is it automatic or interactive?
- Life cycle support (one-shot use to complete cycle support) - How much of the knowledge engineering and system delivery life cycle does the tool support?
- Multiple features / few features - How many techniques are integrated in a single framework? How well do multiple techniques support each other?
- Multiple knowledge sources support - Is there specific support for eliciting, analyzing, or delivering knowledge from multiple experts or other sources?
- Multiple knowledge views / few knowledge views - How many ways are there to look at elicited knowledge? What, if any, knowledge transformation techniques are employed?
- System in use / system not in use - Is the tool currently in use? Was the tool previously in use? Will the tool be in use in the future?
- Training needed - How much training is needed to use the tool? Can experts use the tool directly?
- Users (end-users of expert system, decision makers, experts, knowledge engineers, AI programmers needed) - Who are the targeted users of the tool?

Modeling dimensions
- Deep modeling / shallow modeling - Are "deep" models or "causal" models elicited?
- Multiple / single methods for handling uncertainty - What techniques, if any, are used to model uncertainty?

AQUINAS performed several analyses of the knowledge. For example, an implication analysis produced by AQUINAS showed logical entailments between different dimensions (Figure 3). A similarity analysis among dimensions showed, for example, that EFFICIENT.AND.FAST.TO.USE was closely coupled to LITTLE.TRAINING.NEEDED. A similarity analysis among tools showed, for example, high similarity between ETS, KITTEN, and PLANET, and low similarity between FIS and KSS1 (similarity scores were produced for each pair of dimensions and each pair of tools).

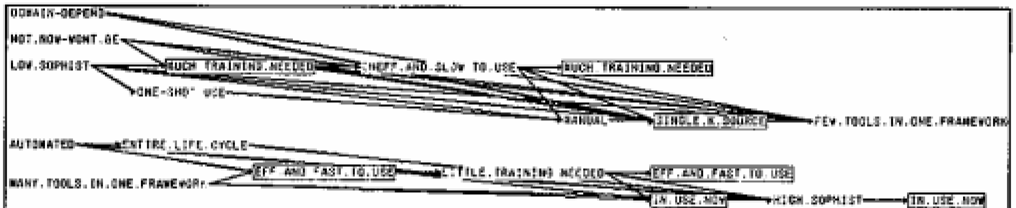
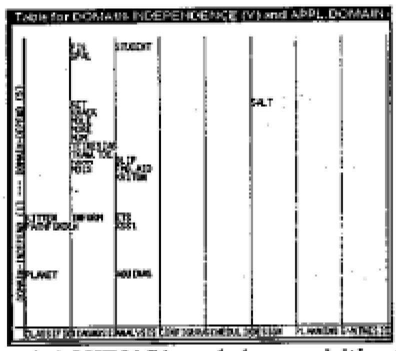


Figure 3. AQUINAS was used to produce implications showing logical entailment graphs and listings between tool dimensions.

AQUINAS also produced several "scatter tables" showing clusters of tools plotted on successive pairs of dimensions. Figure 4 (domain independence vs. task class) shows strong concentrations of knowledge acquisition tools for diagnostic tasks, but few knowledge acquisition tools for synthesis problems. Figure 5 shows that, generally, it is easier to automate tools that are more domain-dependent. Figure 6 shows that, generally, automated knowledge acquisition tools are easier to learn how to use. Figure 7 shows that knowledge acquisition tools that support more of the knowledge engineering life cycle tend to be more domain-dependent.



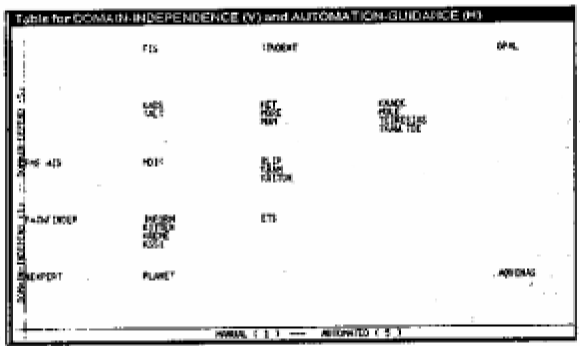


Figure 4. AQUINAS knowledge acquisition tool scatter table for domain independence vs. task class.
Figure 5. AQUINAS knowledge acquisition tool scatter table for domain dependence vs. degree of knowledge acquisition process automation.

Figure 6. AQUINAS knowledge acquisition tool scatter table for degree of KA process automation vs. amount of training needed to use tool effectively.

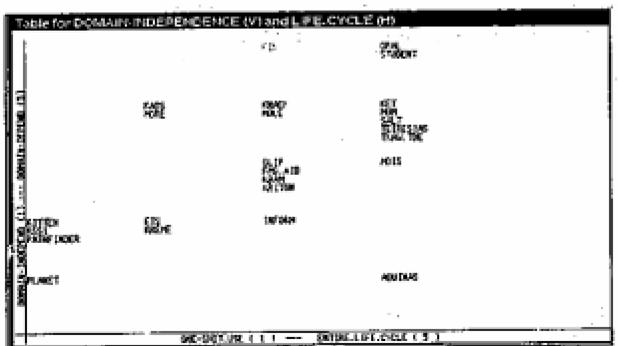


Figure 7. AQUINAS knowledge acquisition tool scatter table for domain independence vs. knowledge engineering life cycle support.

Other patterns in the tools are apparent. For instance, some tools try to draw power using strong specific domain knowledge (FIS, STUDENT, OPAL, MUM); other tools try to address a broader range of problems at the expense of some problem-solving power (ETS, KITTEN, AQUINAS). The few tools that address synthesis problems are domain dependent. Most researchers seem to be interested in applying their tools to more domain independent and/or harder tasks.

3.2 Knowledge Acquisition Techniques and Methods

In this section, knowledge acquisition methods and techniques presented at various Knowledge Acquisition Workshops are listed and briefly described. Techniques are divided into *manual* techniques and *computer-based* techniques. Computer-based techniques and tools are further divided into *interview-based*, *learning-based*, and miscellaneous techniques and tools. This section is meant to serve as a reference for those interested in obtaining more information about these techniques and tools.

Several papers discuss issues such as the future of knowledge acquisition systems and the evolving nature of the knowledge engineering process (Gaines, 1987a,1987b, 1988a, 1988b).

3.2.1 . Manual Techniques

Interviewing

Unstructured Interview - *ask general questions and hope for the best, recording as much as possible*
(Kidd and Cooper, 1985), (Freeman, 1985), (Trimble, 1987), (Welbank, 1987a)

Focussed Interview - *interview with open questions and a list of topics to cover*
(Bradshaw, 1988), (Welbank, 1987b)

Structured Interview - *interview with strict agenda and list of specific questions relating to features of system*
(Bradshaw, 1988), (Freiling, Alexander, Messick, Rehfuss, and Shulman, 1985), (Slocombe, Moore, and Zelouf, 1986)

Active Knowledge Engineer Roles

Participant Observation - *knowledge engineer becomes an apprentice or otherwise participates in the expert's problem-solving process*
(Welbank, 1987b)

Teachback Interview - *knowledge engineer demonstrates understanding of expertise by paraphrasing or solving a problem*
(Johnson and Johnson, 1987)

Tutorial Interview - *expert delivers a lecture*
(Welbank, 1987b)

Brainstorming

Crawford Slip Method - *rapidly generate a large number of ideas*
(Rusk and Krone, 1984)

Psychology-based

Card Sorting - *sort objects on cards to help structure knowledge*
(Gammack and Young, 1984, in Welbank, 1987b)

Psychological Scaling (including multidimensional scaling) - *use scaling techniques to help structure knowledge*
(Burton, Shadbolt, Hedgecock, and Rugg, 1987) , (Saaty, 1981), (Young and Gammack, 1987)

Overcoming Bias - *recognize and correct bias from knowledge sources*
(Cleaves, 1987) , (Moray, 1985), (Stephanou, 1987)

Protocol Analysis (Case Walk-Through / Eidetic Reduction / Observation / Process-Tracing) - *record and analyze transcripts from experts thinking aloud during tasks*
(Belkin, Brooks, and Daniels, 1987) , (Breuker and Wielinga, 1987b), (Ericcson and Simon, 1984), (Gammack and Young, 1984, in Welbank, 1987b) , (Grover, 1983) , (Johnson, Nachtsheim, and Zualkernan, 1987) , (Killin and Hickman, 1986), (Littman, 1987), (Waldron, 1985) , (Wetter and Schmalhofer, 1988)

Uncertain Information Elicitation - *expert encodes uncertainty about the problem*
(Beyth-Marom and Dekel, 1985), (Hink and Woods, 1987), (Kahneman, Slovic, and Tversky, 1982), (Pearl, 1986), (Shafer and Tversky, 1985), (Spetzler and Stael von Holstein, 1983), (Stael von Holstein and Matheson, 1978), (Tversky, Sattah, and Slovic, 1987), (Wallsten and Budescu, 1983)

Wizard of Oz Technique - *an expert simulates the behavior of a future system*
(Sandberg, Winkels, and Breuker, 1988)

3.1.2 Computer-Based Techniques

When specific computer-based tools implement these methods, the name of the tool is listed. Computer-based tools are described and referenced below. Work describing methods not implemented as computer-based tools are listed and referenced as a "Method."

Interview-Based and Miscellaneous Techniques

Psychology-Based and Interviewing Methods

Automated / Mixed-initiative Interviewing - *the tool interviews the expert*
AQUINAS, ASK, CAP, ETS, KITTEN, KNACK, KRIMB, KRITON, KSS1, MDIS, MOLE, MORE, ODYSSEUS, PLANE, PROTOS, ROGET, SALT, TEIRESIAS, TKAW

Protocol Analysis (Case Walk-Through / Eidetic Reduction / Observation / Process-Tracing) - *record and analyze transcripts from experts thinking aloud during tasks*
KRITON, LAPS, MEDKAT

Psychological Scaling (including multidimensional scaling) - *use scaling techniques to help structure knowledge*
AQUINAS, KITTEN, KSS1, PATHFINDER, PLANET
Methods - (Butler and Corter, 1986), (Gaines and Shaw, 1981), (Kelly, 1955)

Repertory Grids / PCP - *use personal construct psychology and related methods to elicit and analyze knowledge*
AQUINAS, ETS, FMS-AID, KITTEN, KRITON, KSS1, PLANET

Task / Method / Performance Exploitation

Domain Exploitation (Single Application) - *rely heavily on the domain for knowledge acquisition guidance*
FIS, LAS, LEAP, OPAL, PROTOGE', STUDENT

Problem-Solving Method Exploitation - *use information about the problem-solving method to guide knowledge acquisition*
AQUINAS, CLASSIKA, FMS-AID, KNACK, MDIS, MOLE, MORE, SALT, TEIRESIAS, TKAW

Performance System *(direct link or embedded)* - *generate knowledge that may be directly tested*

AQUINAS, ASK, BLIP, ETS, KAE, KNACK, KRITON, LAPS, LEAP, MDIS, MOLE, MORE, MUM, ODYSSEUS, OPAL, PROTOGE', ROGET, TEIRESIAS, TKAW, SALT

Modeling

Decision Analysis - *perform probabilistic inference and planning using influence diagrams*
INFORM
Methods - (Bradshaw and Boose, 1988), (von Winterfeldt and Edwards, 1986)

Modeling *(deep models, causal models, cognitive models, conceptual models, mediating representations, task-level models) - use or generate models of the domain, possibly independent of a tool or a specific application*
ASTEK, BLIP, CLASSIKA, FIS, KADS, KRIMB, MACAO, NEXPERT, ONTOS, OPAL, PROTOGE'
Methods - (Addis and Bull, 1988), (Alexander, Freiling, Shulman, Rehfuss, and Messick, 1987), (Hayward, Wielinga, and Breuker, 1987), (Johnson, 1987), (Johnson, Tomlinson, and Johnson, 1988), (Linster, 1987), (Morik, 1987b), (Regoczei and Plantinga, 1987), (Schreiber, Breuker, Bredeweg, and Wielinga, 1988), (Twine, 1988), (Woods and Hollnagel, 1987), (Young and Gammack, 1987)

Consistency Analysis - *analyze knowledge for consistency*
BLIP, FIS, KNAC, MUM, TEIRESIAS

Physical Model Simulation - *use basic laws to derive physical models through simulation*
SIMULA

Multiple Experts

Delphi - *gather information from people independently*
MEDKAT

Multiple Source - *elicit and analyze knowledge from multiple sources separately and combine for use*
AQUINAS, ETS, MEDKAT, KITTEN, KSS1
Methods - (Gaines, 1987a, 1987b), (Mittal and Dym, 1985)

Other Sources of Knowledge

Textual Analysis / Natural Language Analysis - *generate knowledge directly by analyzing text*
KRITON, KSS1, KBAM, PSOPOS/EPISTOS, WASTL

Learning-Based Techniques

Analogy - *apply knowledge from old situations in similar new situations*
CYC, TEIRESIAS

Apprenticeship Learning - *learn by watching experts solve problems*
DICIPLE, ISG, LEAP, LEDA, ODYSSEUS, PROTOS, OPAL, STUDENT

Decision Tree Induction / Analysis; Question Scheduling - *generate, analyze decision trees*
CART, ID3
Methods - (Bramer, 1987), (Cox, 1988), (Goodman and Smyth, 1988), (Pettit and Pettit, 1987)

Example Selection - *select an appropriate set of examples for various learning techniques*
Methods - (Blythe, Corsi, and Needham, 1987), (Rissland, 1988)

Explanation-Based Learning - *deduce a general rule from a single example by relating it to an existing theory*
ACES, INDE, LAS, LEAP, OCCAM, ODYSSEUS, SRAR
Method - (Kodratoff, 1987a, 1987b)

Genetic Algorithm - *genetic operators (crossing-over, mutation, inversion) are used to adapt a system's behavior*
Method - (Pettit and Pettit, 1987)

Induction of Models from Experience
AM, ATOM

Mimicking Expert Behavior
INDUCE

Performance Feedback - *performance feedback is used to reinforce behavior*
AQUINAS, MOLE, PERCEPTRON, PROTOS, STELLA

Rule / Knowledge Induction - *generate rules from other forms of knowledge*
AQ, AQUINAS, BLIP, ETS, KSS1, INSTIL
Methods - (Buntine, 1987), (Cleary, 1987), (Delgrande, 1987), (Goodman and Smyth, 1988), (Rissland, 1988), (Sebag and Schoenauer, 1988), (Witten and MacDonald, 1988)

Similarity-Based Learning - *learn similarities from sets of positive examples and differences from sets of negative examples*
BLIP, GINESYS, ID3, ILROD, INC2, INDE, INSTIL
Method - (Schroder, Niemann, and Sagerer, 1988)

Systemic Principles Derivation - *use general principles to derive specific laws*
OBJ

3.2 Computer-Based Knowledge Acquisition Tools Descriptions and References

Knowledge acquisition tools presented and discussed above are briefly described and referenced here.

ACES - *learn heuristics for fault diagnosis from device descriptions using explanation-based learning* (Pazzani, 1987)
AM - *induce models from experience* (Davis and Lenat, 1982)
AQ - *induce rules from sets of positive and negative training examples* (Michalski, 1983)
AQUINAS - *elicit and model information using a knowledge acquisition workbench including hierarchically-structured repertory grid-based interviewing and testing and other methods* (Boose and Bradshaw, 1987b), (Kitto and Boose,

1987), (Boose and Bradshaw, 1987a), (Boose, 1988), (Bradshaw and Boose, 1988), (Kitto and Boose, 1988), (Shema and Boose, 1988), (Boose, Bradshaw, and Shema, 1988)

ASK - *acquire strategic knowledge from experts using a justification language* (Gruber, 1988)

ASTEK - *combine multiple paradigms for knowledge editing in a natural language discourse framework* (Jacobson and Freiling, 1988)

ATOM - *induce models from experience* (Gaines, 1977)

BLIP - *construct organized domain models automatically by learning from sloppy models* (Morik, 1987a), (Wrobel, 1988), (Kietz, 1988)

CART - *employ cross-validation to produce appropriately-sized decision trees* (Crawford, 1988)

CLASSIKA - *use expert-directed techniques to capture aspects of classification problem-solving* (Gappa, 1988).

CYC - *acquire and use knowledge through the use of analogy and a large existing knowledge base* (Lenat, Prakash and Shepard, 1986)

DICIPLE - *integrate various machine learning techniques to adopt to available theories* (Kodratoff and Tecuci, 1988)

ETS - *interview experts using repertory grid-based methods and test the knowledge* (Boose, 1984, 1985, 1986a, b)

FIS - *tie knowledge acquisition closely to the fault diagnosis domain* (De Jong, 1987)

FMS-AID - *combine repertory grid methods and Newell and Simon's problem space concept to manufacturing problems* (Garg-Janardan and Salvendy, 1987)

GINESYS - use confirmation rules, a form of redundant knowledge, to learn in noisy domains (Gams, 1988).

ID3 - *learn similarities and differences from training sets by optimizing global parameters* (Quinlan, 1983, 1987)

ILROD - *perform logic-based induction on Horn clauses to learn knowledge of relevance* (Dutta, 1988)

INC2 - *perform learning by observation using hill-climbing through a space of hierarchical classification schemes* (Hadzikadic, 1988)

INDE - *generate rules on the basis of counterexamples combining explanation-based learning and similarity-based learning* (Terpstra and Someren, 1988)

INDUCE - *mimic an expert's behavior* (Michalski and Chilausky, 1980)

INFORM - *elicit knowledge using decision analysis techniques* (Moore and Agogino, 1987)

INSTIL - *acquire knowledge using similarity-based learning combining aspects of both numeric and symbolic approaches* (Kodratoff and Manago, 1987a)

ISG - *link evidence to situations by synthesizing rules from interesting situations using an apprenticeship learning approach* (Wisniewski, Winston, Smith, and Kleyn, 1987)

KADS - *elicit and model knowledge decoupled from the design and implementation of the system* (Breuker and Wielinga, 1987a), (Anjewierden, 1987), (Karbach and Tong, 1988), (Schreiber, Breuker, Bredeweg, and Wielinga, 1988)

KAE - *capture scene analysis expertise* (Tranowski, 1988)

KBAM - *use natural language explanations to construct a domain-specific knowledge base* (Silvestro, 1988)

KET - *provide a graphical interface and analyze relationships to help experts write rules* (Esfahani and Teskey, 1987), (Esfahani and Teskey, 1988)

KITTEN - *interview experts using repertory grid-based methods* (Shaw and Gaines, 1987), (Shaw and Woodward, 1988)

KNAC - *use acquired assimilation knowledge to help enter new knowledge in a knowledge base* (Lefkowitz and Lesser, 1988)

KNACK - *elicit and use knowledge about evaluation report generation* (Klinker, Bentolila, Genetet, Grimes, and McDermott, 1987), (Klinker, Genetet, and McDermott, 1988)

KREME - *include multiple-representations in a knowledge editing environment* (Abrett and Burstein, 1987)

KRIMB - *interview experts and build diagnostic domain models* (Cox and Blumenthal, 1987)

KRITON - *combine repertory grid interviewing and protocol analysis to build knowledge at an intermediate level* (Diederich, Ruhmann, and May, 1987), (Diederich, Linster, Ruhmann, and Uthmann, 1987), (Linster, 1988)

KSS0 - *elicit knowledge with a repertory grid-based interviewing tool including text analysis, behavior induction, and psychological scaling techniques* (Gaines, 1987a, 1987b, 1988), (Gaines and Sharp, 1987), (Shaw and Gaines, 1987), (Shaw, 1988)

LAPS - *interweave protocol analysis completeness querying* (di Piazza, 1988)

LAS - *use apprenticeship learning to learn by watching experts solve problems* (Smith, Winston, Mitchell, and Buchanan, 1985)

LEAP - *use apprenticeship learning to learn steps in VLSI design by watching experts solve problems* (Mitchell, Mahadevan, and Steinberg, 1985)

LEDA - *acquire knowledge for chip architecture design by interactively generalizing design plans* (Herrmann and Franzke, 1988)

MACAO - *model expert knowledge based on empirical and conceptual schemes* (Aussenac, Frontin, and Soubie, 1988)

MDIS - *experts are interviewed to describe mechanisms in a top-down structured manner for diagnostic problems* (Antonelli, 1983)

MEDKAT - *automate the Delphi technique to gather information from multiple experts* (Jagannathan and Elmaghraby, 1985).

MOLE - *exploit information about how problems are solved to elicit scarce diagnostic knowledge and use feedback to fine tune the knowledge* (Eshelman, Ehret, McDermott, and Tan, 1987), (Eshelman, 1988)

MORE - *exploit information about how problems are solved to elicit extensive diagnostic knowledge* (Kahn, Nowlan, McDermott, 1985a,b)

MUM - *evidential combination knowledge and control knowledge are elicited for medical problems* (Gruber and Cohen, 1987)

NEXPERT - *include multiple-representations in a knowledge editing environment with a performance component* (Rappaport, 1987), (Rappaport, 1988)

OBJ - *use general principles to derive specific laws* (Goguen and Meseguer, 1983)

OCCAM - *learn to predict outcomes of economic sanction episodes using explanation-based learning* (Pazzani, 1987)

ODYSSEUS - *refine and debug knowledge using apprenticeship learning techniques* (Wilkens, Clancey, and Buchanan, 1987)

ONTOS - *build domain models using cognitive and linguistic factors* (Monarch and Nirenburg, 1987)

OPAL - *tie knowledge acquisition closely to the cancer treatment domain* (Musen, Fagan, Combs, and Shortliffe, 1987)

PATHFINDER - *use psychological scaling techniques to help structure knowledge hierarchically* (Cooke and McDonald, 1987)
PLANET - *use repertory grids for psychological interviewing and analysis* (Shaw, 1984), (Gaines, and Shaw, 1986)
PROPOS/EPISTOS - *transform text into a meaning representation and then perform epistemological analysis using pragmatic fields* (Moller, 1988)
PROTOGE' - *edit the conceptual model of another knowledge acquisition tool (OPAL) for skeletal plan refinement tasks* (Musen, 1988)
PROTOS - *use exemplar-based learning in an apprenticeship learning system* (Bareiss, Porter, and Wier, 1988)
ROGET - *interview experts and produce conceptual structures of the domain* (Bennet, 1985)
SALT - *elicit and deliver knowledge for constructive constraint satisfaction tasks* (Marcus, McDermott, and Wang, 1985), (Marcus, 1987), (Stout, Caplain, Marcus, and McDermott, 1988)
SIMULA - *use basic laws to derive physical models through simulation* (Nygaard and Dahl, 1981)
SRAR - use explanation-based learning techniques to develop intelligent tutoring systems (Guy and Nuss, 1988).
STELLA - *performance feedback is used to reinforce behavior* (Gaines and Andreae, 1966)
STUDENT - *tie knowledge acquisition closely to the statistical consulting domain* (Gale, 1987)
TEIRESIAS - *model existing knowledge to monitor refinements and help debug consultations* (Davis and Lenat, 1982)
TKAW/TDE - *exploit information about how problems are solved to elicit trouble-shooting knowledge* (Kahn, Breaux, Joeseph, and DeKlerk, 1987)
WASTL - *acquire knowledge for a natural language understanding system based on KADS methodology* (Jansen-Winkeln, 1988)

4 DISCUSSION

The first part of this paper presented a framework for associating knowledge acquisition tools with knowledge-based application tasks and problem-solving methods. Specific tools and tool classes were associated with specific application tasks and methods (i.e., AQUINAS is associated with analysis tasks and the heuristic problem-solving method; SALT is associated with configuration and design applications and a specialized form of backtracking).

These associations help define the depth and breadth of current knowledge acquisition research. Our research using AQUINAS has led us to try and build a broad link (multiple integrated tool sets) between a general application task class (analysis problems) and a powerful problem-solving method (heuristic classification). Other successful work has led researchers to tightly couple knowledge acquisition tools to a domain task (for example, FIS, STUDENT, OPAL).

Current research strategies were mentioned. Associations in the task-method framework where no tools exist can point out promising areas for new research. Can special forms of knowledge acquisition tools be associated with debugging tasks and heuristic classification, or planning and new specializations of backtracking?

This descriptive approach provides a framework for studying and comparing tools. It also emphasizes the need for a more refined application task hierarchy, and the need to recognize and generalize new problem-solving methods.

The rest of the paper analyzed dimensions and relationships among the tools and techniques, and classified and briefly described current knowledge acquisition tools and methods. It is hoped that this reference work will be useful both as an introduction and to those are pursue this field of research.

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This document will be periodically updated and re-published. If you have additional information or revisions concerning knowledge acquisition tools and techniques, please notify the author.

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The *Proceedings of the First European Workshop on Knowledge Acquisition*, Reading, U.K, September 1-3, 1987, will be published in an Academic Press book in 1988. Copies of the proceedings distributed at the workshop are available directly from Tom Addis, Department of Computer Science, Reading University, Whiteknights, PO Box 220, Reading RG6 2AX, U.K. for 39 pounds (Tom Addis@reading.ac.uk).

The *Proceedings of the Second European Workshop on Knowledge Acquisition*, Bonn, June 19-32, 1988, will probably be published in an Academic Press book in late 1988. Copies of the proceedings distributed at the workshop are available directly from Marc Linster, Institut for Applied Information Technology, German Research Institut for Mathematics and Dataprocessing, Schloss Birlinghoven, Postfach 1240, D-5205 St. Augustin 1, West Germany (GMD will invoice you for DM68.00 plus postage).

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