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13. ABSTRACT (Maximum 200 words)

The primary objective of this project has been the development of systems that reason in dynamic and open-ended environment and that use networks as their primary representation language. The focus of our research has been temporal reasoning, neural networks, truth maintenance, and default reasoning. This investigation has led to several basic results: the expressiveness of constraint networks was analyzed, tractable classes of constraint satisfaction problems were identified and effective processing techniques were developed.

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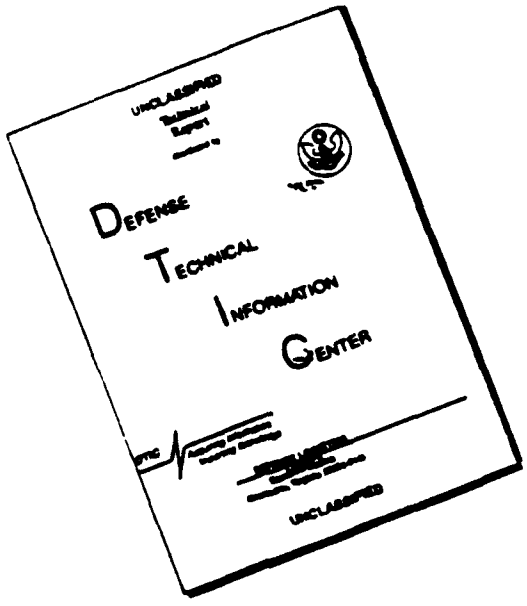

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Mr. Goldenberg:
Enclosed is the final technical report for Dr. Pearl's AFSOR 90-0136. This delinquent report was holding up Dr. Davis's AAASERT grant start date of 2/4/94 for $156,915.

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SUMMARY OF RESEARCH RESULTS

Specifically, the following results were obtained during the period of performance:

1. Theoretical limits were obtained on the expressiveness of constraint networks that contain hidden variables. Trade-offs were established between the number of hidden variables required and the size of their domain to ensure that an arbitrary relation be expressible as a constraint network. Similar relationships were developed between the sizes of the variables domain and the level of local consistency to ensure global consistency.
2. Distributed, self-stabilizing algorithms were developed for solving a general network consistency problem, and for performing truth-maintenance tasks on singly-connected structures. Effective methods were developed for combining qualitative and quantitative information for temporal reasoning.
3. New applications of constraint networks were identified in the area of default reasoning, leading to new effective algorithms and tractable sublanguages for representing defeasible information.
4. A new framework was developed for planning under uncertainty, combining causal networks, qualitative probabilities, and qualitative utilities.

Results listed under items 1 and 2 above are described in the accompanying list of publications. The following is an elaboration of recent achievements summarized under items 3 and 4 above.

Default reasoning with constraint networks

The main goal of this project has been to identify the features that render certain classes of non-monotonic theories tractable, and to implement our findings in a working system. The approach has been to map default theories into well understood languages such as propositional logic and constraint networks so as to transfer semantics and techniques from the latter to the former.

The approach was pursued by Rachel Ben-Eliyahu (PhD, July 1993) and has led to remarkable results, summarized in six publications. Basically Rachel has shown that, contrary to prevailing folklore and some unrealistic theoretical results, practical non-monotonic reasoning need not be harder than monotonic reasoning. She has found a way of translating non-monotonic tasks to propositional theories such that queries (about membership and entailment) posed in the former framework can be answered by the latter.

We believe these results will have a significant impact on the eventual (and inevitable) implementation of commonsense reasoning in practical computer systems. Our more recent explorations aim at finding a translation (using Clark's completion) that will permit the implementation of default logic in existing PROLOG systems.

Qualitative planning under uncertainty

Most real-world knowledge is expressed qualitatively yet it is processed by principles other than those of classical logic. World knowledge include, for example, the typical properties of objects and classes, what an agent should expect given facts observed in the world, and how the world would react to actions taken by the agent. Such facts and expectations, are usually expressed in the form of logical sentences which tolerate exceptions and there has been a long tension between the logical and probabilistic approaches of processing such sentences.

The method of qualitative probabilities we have been developing in the past few years (first with H. Geffner (PhD, 1990) and more recently with M. Goldszmidt (PhD, 1992)) provides ways of combining logic and probabilities so as to achieve the benefits of both. With the aid of this method it became possible to derive natural priorities among conflicting sentences, and to answer queries without computing explicit rankings of models or formulas. The result is a semi-tractable account of plausible beliefs which, as in classical logic, are qualitative and deductively closed and, as in probability, are subject to retraction and to varying degrees of firmness.

A major progress along this research is the successful incorporation of causal expressions, which has been an embarrassing stumbling block in all non-monotonic systems. This last step has provided a genuine qualitative counterpart to probabilistic networks and now offers a unifying framework for performing prediction, abduction, inheritance, and control. Our most recent achievement toward a fully autonomous reasoning agent has been the development of a qualitative decision theory which combines qualitative information about utilities and likelihood, thus providing the basis for qualitative planning under uncertainty.

The surprising aspect of our finding has been the economy and simplicity of the knowledge required for implementing this scheme. In particular, we have shown that adding a single causal network as part of the agent knowledge base is sufficient for specifying the dynamics of beliefs under any sequence of actions and observations, thus facilitating the analysis of actions, their consequences, their interaction with observations, their expected utilities and, hence, the synthesis of plans and strategies under uncertainty.

In summary, we have developed a comprehensive framework for a practical autonomous reasoning agent that is unique in several respects: It is grounded in sound probabilistic semantics, it is tractable for many practical purposes, and it is versatile, incorporating variable-strength expressions, pooling of evidence, actions, cause-effect relationships and utility information. We believe that this system will be the front runner in applications involving sensor interpretation planning, and control.

List of Publications Resulting from the AFOSR Award

Geiger, D. and Pearl, J., "Logical and Algorithmic Properties of Conditional Independence and Graph Separation," *The Annals of Statistics*, December 1993.

Pearl, J., "From Adams Conditionals to Default Expressions, Causal Conditionals, and Counterfactuals," forthcoming in B. Skyrms (Ed.), *Festschrift for Ernest Adams*, Cambridge University Press, 1993.

Pearl, J., "Aspects of Graphical Models Connected With Causality," to be presented at the *49th Session of the International Statistical Institute*, Florence, Italy, August25 - September 2, 1993.

Pearl, J., "Graphical Models, Causality, and Intervention," Comments on: 'Linear Dependencies Represented by Chain Graphics' by Cox, D. and Wermuth, N., and 'Bayesian Analysis in Expert Systems' by Spiegelhalter, Dawid, Lauritzen, and Cowell, in *Statistical Science*, 266-269, August 1993.

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List of Students Supported by the AFOSR Award

Alex Balke

Rachel Ben-Eliyahu (PhD, July 1993), "Nonmonotonic Reasoning in Classical Logic."

Huy Cao

Dan Geiger (PhD, 1990) "Graphoids: A Qualitative Framework for Probabilistic Inference."

Moises Goldszmidt (PhD, December 1992), "Qualitative Probabilities: A Normative Framework for Commonsense Reasoning."

Jim Kan

Itay Meiri (PhD, January 1992), "Temporal Reasoning: A Constraint-Based Approach."

Sek-Wah Tan

Mitchell Tsai

Thomas Verma (degree expected: PhD, Winter 1994)

Amir Weinshtain (MS, 1991)