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Both AI and Cognitive Science must deal with uncertainty much of the time. To cope with this problem, new systems are being developed in AI for representing and propagating subjective belief using semantic nets. In these systems, propagation of uncertainty goes on while logical inferences are drawn. Cognitive scientists may find these methods useful for applications in learning and problem-solving, so this paper will describe the nature of the tools and mention some examples of applications.

There is a long history of attempts by logicians and mathematicians to represent human reasoning more or less realistically. Two basic methods have been employed. One approach is the path of inference, the drawing of conclusions from "givens". The other is the path of likelihood, the estimation of certainty on the basis of experience of some kind. The first theories to be solidly founded have been formal mathematical logic and the theory of probability. Unfortunately, formal logic applies only to a narrow class of situations, and most human reasoning is outside its scope. Similarly, to be applied, probability often demands knowledge not possessed by people. What would be most desirable would be a wedding of inference and likelihood, so that degrees of ignorance could be associated with assertions without requiring unavailable knowledge.

In order to make the contributions of the new methods clearer, we shall describe the nature of the modelling limitations in the older formalisms. Logics such as propositional calculus and first-order predicate calculus demand certainty of belief in the truth or falsity of assertions. In addition, they are monotonic; i.e., they are unable to alter beliefs once established, and also possess no representation of passage of time. One by one these modelling limitatations are being overcome. A variety of non-monotonic logics have been developed which permit the altering of established beliefs. They do this by representing the passage of time in successive "context" layers, each of which is a snapshot of the state of belief in the facts of the universe of discourse. As new evidence is introduced, concomitant shifts of belief are permitted and propagated.

Psychologists long ago proved that ordinary human reasoning is often in disagreement with the dictates of strict probability theory. That theory demands knowledge of probability distributions, gathered in a usually laborious fashion. Situations in which the probability of an event depends conditionally on many other events are computed by using Bayes formula. Bayesian statistics requires a knowledge of a large number of probabilities, not often known to the investigator. On the other hand, humans may reason successfully in situations where they are uncertain and possess no statistical or probabilistic knowledge.

The new methods offer the possibility of modelling some aspects of this type of reasoning. The techniques assume a general knowledge of facts and interrelationships while not requiring detailed statistics. They have been developed by modifying logic on the one hand and introducing parameters that replace probability on the other. We shall not mention the numerous logicians who have contributed to what is called confirmation theory. Zadeh, as early as 1965, began the development of "Fuzzy Logic" (Zadeh '65). Some years later, Shortliffe and Buchanan developed a method of representing degrees of subjective belief or disbelief numerically (Shortliffe and Buchanan '75, Shortliffe '76).

Drawing on the work of the confirmation theorists in logic, Shortliffe and Buchanan found a formulation by which they could fulfill certain criteria established by these workers and at the same time draw "reasonable" inferences with which they associated numerical degrees of certainty. Their work was limited to a narrow class of expressions in the propositional calculus. The implementation was monotonic; i.e., belief in a fact could only grow as new supporting evidence was adduced. Contrary evidence also permitted disbelief to grow when that was appropriate. Evidence for and against a hypothesis was weighed by taking the difference between belief and disbelief. In the MYCIN system, they applied a single mode of inference, confirmation, to medical diagnosis, and called it inexact reasoning. Their significant contribution was to provide a means for making logical inferences based on subjective certainties. Exact formulas were given for the propagation of subjective belief. The formulas depended on an initial assignment of belief-transfer coefficients by a human "expert".

My own work has been concerned with generalizing the methods and refining the formulas to apply to arbitrary expressions of the propositional calculus, employing four rules of inference (ponens, tollens, confirmation, and denial) rather than the single confirmation rule. Also, the implementation is a non-monotonic logic, thus permitting both belief and disbelief to fluctuate according to the evidence. The set of logical rules is called plausible inference and the implementation is named the PI system (Friedman '80a, '81). It is a general logical system, reasoning in either direction, unlike MYCIN which was limited to backward chaining of expressions in a simple form. It also has the ability, on the basis of new evidence, to make its own dynamic assignments of belief-transfer coefficients in certain situations. This ability is essential for learning, as the coefficients are a measure of the relevance of one fact to another. The PI system has been applied to fault diagnosis of a spacecraft (Friedman '80b).

While this line of development was taking place, two mathematicians, Dempster and his pupil Shafer, were independently developing a mathematical theory of evidence (Shafer '76). This theory tackled the problem of representing the degree of ignorance and calculating the likelihood of evidence whether based on objective or subjective considerations. By objective we mean based on formal probability. They showed that measures could be devised in a very general way to

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calculate subjective likelihoods. Their formulas had as limiting cases the results of probability theory. Barnett has shown that for certain conditions that apply to our representation, Dempster's general combining formula for the calculation of likelihood or certainty reduces to that employed by Shortliffe and Buchanan, and by myself in plausible inference (Barnett '81). However, Shortliffe and Buchanan's basic formulation was an ad hoc attempt to fit certain logical criteria, so both their rules and those of plausible inference lack a solid mathematical foundation in the computation of belief. Shafer's work shows that the present rules of plausible inference are applicable only for a restricted set of cases, but also provides the information that makes it possible to augment the rules so that it is applicable to most cases of interest, and solidly founded.

For his thesis, a doctoral candidate in AI, John Lowrance, is applying Dempster and Shafer's work to a problem in vision. Recently he and several co-workers have drafted a paper that applies the Dempster and Shafer rules to a different problem (Garvey, Lowrance and Fischler '81). They are estimating the source of a given set of noisy measurements when the origin of those measurements comes from one of a known set of emitters. The measurements are combined to give the degree of support and the uncertainty associated with the evidence for each emitter before that belief is propagated to other assertions via inference.

Such quantities are exactly what is needed. in completely automated diagnostic or decision-making inference systems that must deal with uncertainty. The measuring devices would feed degree of belief into assertions linked into a knowledge base, and by plausible inference the knowledge base could draw conclusions about what to do or what went wrong. Garvey, Lowrance and Fischler also point out the possibility of constructing an evidential propositional calculus similar to plausible inference, and suggest coupling the measured estimates based on Dempster's rule with such an inference system.

Summing up, extensions to both formal logic and likelihood theory are converging. The representation and propagation of subjective uncertainty in a knowledge base have been reduced to a set of logical and computational procedures which have propositional calculus as a limiting case. Earlier attempts in cognitive science to model such phenomena include Colby's model of paranoia implemented in PARRY (Colby '73), and Rieger's use of inference to model language understanding (Rieger '76). The new methods have already been applied to a variety of problems in diagnosis, vision analysis, and noisy measurement. Their application to learning as a problem solving activity appears attractive. Further developments in the theory may be possible such as a modification of first order predicate calculus that represents uncertainty.

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