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USING STEP-LOGIC FOR TRACTABLE NON-MONOTONIC INFERENCE---RESEARCH SUMMARY*

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1 Introduction

Because humans must deal in a world about which we have incomplete knowledge, humans often use *default reasoning*: in the absence of information to the contrary assume such and such. For example, upon being told that Tweety is a bird, and knowing that typically birds fly, we might conclude that Tweety flies. When we then discover that Tweety is in fact a penguin (and knowing that penguins typically do not fly), we retract our belief that Tweety flies. Humans do this type of inferencing all the time. However, formalizing default reasoning is not so straightforward. Before we draw our desired conclusion, we must determine that the conclusion is in fact consistent with our current set of beliefs. This means that not only must its negation not appear in the belief set, but also---and this is the crux of the problem---its negation must not be logically entailed by the current set of beliefs. There is no general procedure for determining whether a given belief is consistent with a set of beliefs. This is the *consistency check* problem.

Step-logic was developed in [Elgot-Drapkin, 1988] as a formal mechanism for modeling the *ongoing* process of reasoning. Unlike traditional logical formalisms, step-logic does not calculate a *final* set of conclusions which can be drawn from an initial set of facts, but rather monitors the ever-changing set of conclusions as time goes on. This is done by regarding the reasoning process as occurring over a sequence of steps. It is not some ultimate state that we are interested in, but rather the sequence of steps as we progress in time. This gives step-logic some rather interesting and profound properties.

With respect to default reasoning, perhaps the most important property of step-logic is that, unlike traditional logics, step-logic can tolerate contradictions. A chief drawback of more traditional logics is what we call the *swamping problem*: from a contradiction all wffs come to be theorems.[1] In step-logic, however, it is not at all critical whether a contradiction is *instantly* resolved. Inferences are drawn step-by-step, and hence the possible spread of invalid conclusions based on a contradiction also occurs only step-by-step. This makes it possible to effectively control the spread.

Much of the original motivation for non-monotonic reasoning formalisms stressed the importance of being able to jump to default conclusions quickly. Little of the formal work, however, has actually justified this claim; existing formal theories only come part-way toward achieving this goal, depending upon some outside oracle for the all-too-important consistency check. Step-logic, in contrast, does not require this consistency check---contradictions are allowed to occur. This has profound consequences in the area of non-monotonic reasoning, which we shall describe below.

The literature contains a number of approaches to limited reasoning. See [Konolige, 1984, Levesque, 1984, Fagin and Halpern, 1988, Lakemeyer, 1986, Vardi, 1986]. Although these approaches all model *limited* reasoning, the process is still in terms of the standard mold of *static* reasoning. There is indeed a restricted view of what counts as a theorem, but the logic still emphasizes the final state of reasoning. The effort involved in actually performing the deductions is not taken into consideration. Since step-logic models the ongoing process of deduction, there is no final state of reasoning; there is only the ever-changing set of conclusions as time goes on.

Section 2 describes step-logic and how it is fundamentally different from other non-monotonic formalisms. We give an example of how step-logic can be used for tractable default reasoning in Section 3. Section 4 summarizes the main points of the paper.

*See [Perlis *et al.*, 1991, Elgot-Drapkin, 1988, Elgot-Drapkin and Perlis, 1990, Elgot-Drapkin *et al.*, 1991, Elgot-Drapkin, 1992] for a more comprehensive description of the issues addressed here.

[1] This is not a problem in *implementations* of standard logics, however, since the theorems of the logic are not all drawn instantaneously.

2 Step-logic versus other Non-monotonic Reasoning Formalisms

Step-logic is a model of reasoning that focuses on the ongoing process of deduction. In step-logic, the reasoner being modeled starts out with an empty set of beliefs at step 0. *Observations* (that is, external inputs to the system) may arise at discrete time-steps. These are the *axioms* in a traditional logic. When an observation appears, it is considered a belief. From these beliefs, new beliefs may be concluded. So at some step i the reasoner may have belief α, concluded based on earlier beliefs or arising at step i directly as an observation. Since the process of deduction is part of the same reasoning, these time parameters can figure in the on-going reasoning itself. Because of this, the step-logic cannot in general retain or inherit all conclusions from one step to the next. In particular we see this with any wffs dealing with the notion of ''now''. As an example, we might see $Now(i)$, intuitively ''the time is now i'', as a conclusion at step i. At some later step j, the reasoner might no longer have the belief $Now(i)$, but would now believe $Now(j)$. If certain wffs are to be inherited from one step to the next, this must be explicitly stated in an inference rule. In several versions of step-logic used for various commonsense reasoning problems, everything except direct contradictions and $Now(i)$ are inherited. See [Elgot-Drapkin, 1988].

Viewing reasoning in this way affords a great advantage: because all the reasoning is done only a step at a time, the beliefs that one currently holds can be kept finite. With a finite set of beliefs, it is possible for the reasoner to introspect on his set of beliefs. Negative introspection refers to the process of introspecting on one's beliefs to determine if some belief is *not* there. For instance, ''I do not know Tweety is a penguin.'' can be concluded after looking at one's beliefs and determining that ''Tweety is a penguin.'' is not among the beliefs. Note we only need to determine whether ''Tweety is a penguin.'' is among the beliefs, not whether it is a logical consequence of the belief set. This is because of the step-like nature of the step-logic formalism. This is what makes negative introspection tractable.

Once negative introspection is tractable, default reasoning based on negative introspection (''If I don't know x, then conclude y.'') becomes tractable. The non-monotonic formalizations presented in [McCarthy, 1980, Reiter, 1980, McDermott and Doyle, 1980, Moore, 1983] are not tractable for they all require some sort of a consistency check (or its equivalent) to be done in order to make a default conclusion. Step-logic, in contrast, provides a tractable non-monotonic formalism.

In [Ginsberg, 1991] it is pointed out that although the original motivation for the formalization of non-monotonic reasoning stressed the importance of being able to jump to default conclusions quickly, little of the formal work has actually justified this claim. With this in mind, [Ginsberg, 1991] suggests that the consistency check problem can be alleviated by breaking up the original problem into two smaller ones. (Since the complexity is algorithmic, it is far more efficient to solve two smaller problems than one larger one.) Default assumptions are used to focus this process. Although this technique provides a method of making non-monotonic reasoning tractable, the technique still requires a proof that the default conclusion is valid (provable). In the step-logic approach, no validity proofs are necessary.

The consistency checking process can also be tackled by allowing the reasoning system to assert its desired conclusion and then running a routine to resolve any inconsistencies that may have arisen as a result of the conclusion having been added. [Doyle, 1979] and [deKleer, 1986] provide such methods of handling contradictions to ensure that consistency is maintained. The lengthy process, however, is seen to be separate from the non-monotonic reasoner.

In contrast to Doyle and deKleer, step-logic actually allows contradictions. Because conclusions are drawn step-by-step, the possible spread of invalid conclusions based on a contradiction occurs only step-by-step. Thus it is possible to effectively control the spread. Currently step-logic handles the consistency issue by allowing inconsistencies to persist. It is only direct contradictions that are resolved. In addition, in contrast to the methods of inconsistency resolution in [Doyle, 1979] and [deKleer, 1986], step-logic treats the process of resolving inconsistencies as part of that very same reasoning process. Thus this resolution proceeds concurrently with the remainder of the reasoning process. That is, our method takes into consideration that resolving these conflicts is a process, and as such, takes time to complete. We therefore have a trade-off between resolving our contradictions *quickly* versus *completely*. (Recall inconsistencies do not need to be totally removed!)

For more background on step-logic, see [Elgot-Drapkin, 1988, Drapkin and Perlis, 1986, Elgot-Drapkin and Perlis, 1990].

3 Default Reasoning Example

We illustrate in this section how step-logic can be used as a tractable model of default reasoning. In [Moore, 1983] the following problem is presented:

> Consider my reason for believing that I do not have an older brother. It is surely not that one of my parents once casually remarked, ''you know, you don't have any older brothers,'' nor have I pieced it together by carefully sifting other evidence. I simply believe that if I had an older brother I would surely know about it.

To solve this problem one must be able to reason, ''since I don't know I have an older brother, I must not.'' This problem can be broken down into two: the first requires that the reasoner be able to decide he doesn't know he has an older brother; the second that, on that basis, he, in fact, does not have an older brother (from *modus ponens* and the assumption that ''If I had an older brother, I'd know it.'').

It is easy enough to provide a model of reasoning to account for this latter part of the problem. It is the former part, however, that is more difficult. The reasoner must be able to determine that he doesn't know a particular piece of information. This is the consistency check problem mentioned above. Step-logic, with its finite introspective capabilities, allows this determination to be made within the formalism itself. The step-logic reasoner is able to introspect and determine that he does not have the knowledge of an older brother. With the rule, ''If I have an older brother, I know I have an older brother,'' the reasoner can then deduce that he, in fact, does not have an older brother. This problem is tackled in detail in [Elgot-Drapkin, 1988, Elgot-Drapkin and Perlis, 1990], where both a formal solution and an implementation of that solution are given. Here we merely describe several different aspects of the problem.

Let B be a 0-argument predicate letter representing the proposition that an older brother exists. Let P be a 0-argument predicate letter (other than B) that represents a proposition that implies that an older brother exists.[2] In each case, at some step i the agent has the axiom $P \rightarrow B$, and also the following autoepistemic axiom which represents the belief that not knowing B ''now'' implies its negation.

Axiom 1 $(\forall x)[(Now(x) \wedge \neg K(x-1, B)) \rightarrow \neg B]$[3]

We can think of this axiom as saying, ''If I don't know I have an older brother, then I must not.''

The following behaviors are illustrated in detail in [Elgot-Drapkin, 1988, Elgot-Drapkin and Perlis, 1990]:

- If B is among the wffs of which the agent is aware at step i, but not one that is believed at step i, then the agent will come to know this fact ($\neg K(i, B)$, that it was not believed at step i) at step $i+1$. As a consequence of this, other information may be deduced. In this case, the agent concludes $\neg B$ from the autoepistemic axiom (Axiom 1). The Now predicate plays a critical role here.

- The agent refrains from such negative introspection when in fact B is already known.

- A conflict may occur if something is coming to be known while negative introspection is simultaneously leading to its negation. This conflict is resolved within the step-logic in an intuitive manner.

[2] P might be something like ''My parents have two sons,'' together with appropriate axioms.

[3] The reason for this particular formulation of the autoepistemic axiom is discussed in [Elgot-Drapkin, 1988].

With these examples we see that step-logic is a promising tractable theory for handling simple default cases involving negative introspection, such as the *Brother problem*. When it's appropriate to make the default conclusion (that no older brother exists), the conclusion is indeed inferred. When circumstances should block the default conclusion (when in fact it *is* known that an older brother exists), the conclusion is not inferred. In the third case where self-reflection allows the default inference *at the same time* that another inference leads to the conclusion that an older brother does truly exist, a contradiction results. The logic allows the contradiction to be sorted out; after only a couple of steps the situation stabilizes, with B being believed, and $\neg B$ not being believed.

The key concept to note in this example is that negatively introspecting on one's belief set becomes a tractable task when tackled in a step-logic setting.

4 Summary

Step-logic provides a formalism for tractable non-monotonic reasoning. What makes the step-logic formalism so unique is that the logic explicitly allows unsound inferences (i.e. contradictions can arise). This is done in the interest of efficiency---that is, to avoid the consistency check problem. *No* consistency check is needed to do default reasoning in step-logic! This ability to jump to default conclusions immediately, without the need for a time-consuming consistency check, is a fundamental contribution of step-logic. It is this aspect that makes the step-logic formalism tractable.

The research issues described in this paper have been addressed both in terms of theory as well as implementation.

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