Belief Maintenance in a Natural Language System

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Belief Maintenance Systems manage beliefs and assumptions in a knowledge base, their justifications (reasons for being), and any contradictions that may arise between existing beliefs. Such systems are dependent on strict rules of deductive logic to ensure that the paths between beliefs and their derivations can be traced. However, natural language systems cannot be constrained by the binary nature of truth-conditional logic, and must rely instead on approximate, nondeductive approaches to reasoning. This paper proposes a method for belief maintenance for a natural language system. Based on uncertainty values and the interlinkage of directly asserted and derived propositions, the method provides a means for the postponement of a decision regarding the reason for a contradiction, and includes algorithms that perform nonmonotonic reasoning on a commonsense knowledge base in a manner consistent with humanlike, informal reasoning.

1. Introduction

One of the most critical but least developed areas of Natural Language (NL) research is that of belief maintenance, which involves the management of beliefs and assumptions in a knowledge base, their justifications (reasons for being), and any contradictions that may arise between existing beliefs (see Martins and Shapiro [1] for a discussion of the concept). Most attempts to implement such systems are based on the Truth Maintenance System (TMS) of Doyle [2] and the Assumption-Based Truth Maintenance System (ATMS) of de Kleer [3], the latter improving the efficiency of a TMS by retaining context information in the form of links from all derived propositions to their origins. Unfortunately, no such system has been developed for a general-purpose NL application. Although the TMS concept has been applied in various ways to reasoning and inferencing [4], a NL application must be able to deal with the uncertainties of commonsense reasoning, and to incorporate nonmonotonic logic into the reasoning process to ensure that old conclusions can be changed by new information. The chosen mechanism must be powerful and flexible enough to perform controlled inferencing, detect invalid inferences, and accommodate beliefs that stem from various combinations of predefined premises and derived propositions. It is not yet clear whether a TMS can be applied successfully to such an automated reasoning and understanding device.

This paper describes a partly implemented model for a NL Belief Maintenance System (BMS). Although the model is similar in some respects to the aforementioned work of Doyle and de Kleer, the informal nature of human reasoning prohibits the binary form of belief analysis characteristic of such systems. The method to be described represents an attempt to combine the discrete logic of automated inferencing with the fuzziness of commonsense reasoning. It is implemented as part of the Informational Network for a Natural Thinking (INFANT) System [5], [6], [7], which employs a massive knowledge base of propositional data to represent the changing cognitive states of a child.

2. The INFANT System

The INFANT System is a NL System that demonstrates connectionist-like properties with a massively-interlinked connective network of propositional data. The connective network supports the cross-referencing of stored knowledge necessary for commonsense reasoning. In addition, constantly changing propositional belief values provide the flexibility required by a learning device. Although INFANT is not a connectionist system, it simulates connectionism through its parallel and interconnected architecture, and thereby offers a similar potential for
robustness in its approach to commonsense reasoning.

The INFANT Parser is responsible for the generation of a semantic form that defines in a compact manner the relationships between sentence parts. This is called Hierarchical Logical Form (HLF). As an example, the input sentence

Joe kept the big dog that he found

would result in the HLF

JOE KEPT DOG1

JOE FOUND DOG1 DOG1 BIG

The overall sense of the statement is captured in the top-level proposition, which is entailed by, and further defined by, its subordinate propositions. This concept of subordinate causality was suggested by Frege [8], and further examined by Thompson [9]. The decomposition of sentences into Subject-Predicate-Object propositional triplets is suggestive of Wilks' fragmentation of sentences into Agent-Action-Object template forms [10]. HLF is conceptually related to the theory of propositional linkage advanced by van Dijk and Kintsch [11], who used the term episode to describe a connected series of propositions dominated by a single macroproposition. One significant factor differentiates the INFANT approach from that of van Dijk and Kintsch. Whereas van Dijk and Kintsch reject the notion of simple concept-relation-concept propositions as a standard logical form, the need for efficient data matching in a BMS demands that such uniformity exist in INFANT's stored propositional form. The reduction of complex thoughts to similarly-structured connected units in the INFANT System has simplified the long-term storage and retrieval of knowledge.

3. A Belief Maintenance System for Natural Language Processing

Since natural language lacks the rigorous discipline of logical systems, it must rely instead on approximate, nondeductive approaches to reasoning. Careful analysis of a simple deduction reveals some of the uncertainty common to human thinking. The inference

Mary likes Joe and Bob is not good to Joe; so Mary is not happy with Bob

\[(Vx)(Vy)(Vz)((\text{LIKE}(x,y)) \land (\neg \text{GOOD}(y,z))) \Rightarrow (\neg \text{HAPPY}(x,z))\]

may or may not be believed, or may only be believable to some degree of certainty. The example is an instance of a statistical syllogism, a form of probabilistic reasoning described by Pollock [12]. In addition, a subsequent denial of the conclusion through the statement Mary is happy with Bob may itself not be unequivocally believed. Thus the determination of a reason for the contradiction is hindered by the lack of irrefutable premises and sound inferential logic, and may not even be possible in certain cases.

Various other considerations rule against established methods of belief maintenance for NL Systems. De Kleer's ATMS 'bit map' technique would be difficult to implement in a massive conversational knowledge base, and impractical in the environment of multi-valued logic implied by probabilistic reasoning. Furthermore, if it is true that an assertion in natural language is believed with only some degree of certainty, depending on numerous factors related to context and word usage, later inferences and justifications based on such statements are themselves uncertain.

The INFANT System addresses these issues by employing an 'uncertainty' approach to nonmonotonic reasoning, through which the maintenance of belief states depends on the management of a large number of interacting propositions with varying belief strengths. An interlinked structure of causal antecedents and descendants among propositions allows decisions regarding contradictions to be modified or compromised, or postponed until conclusive evidence becomes available. As discussed earlier, propositions are represented as Agent-Predicate-Object triplets. Predicates are restricted to a small number of primitives (GOOD, HAPPY, PLAY, etc.). A system of belief values (Figure 1) is used to assign belief strengths to the propositions. Thus the propositional form

Mary happy Bob 7

represents the computer's 'belief that Mary is probably happy with Bob'.

Belief values are similar to the compatibility function of Zadeh's fuzzy logic [13]. The actual assignment and long-term management of a belief value is based on an algorithm described in [7].

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9 = CERTAINLY
8 = ALMOST CERTAINLY
7 = PROBABLY
6 = POSSIBLY
5 = UNCERTAIN
4 = POSSIBLY NOT
3 = PROBABLY NOT
2 = ALMOST CERTAINLY NOT
1 = CERTAINLY NOT
0 = NONSENSE

Figure 1 - Uncertainty (Belief) Values
Used in the INFANT System

Various terms and concepts should be defined before a description of the Belief Maintenance algorithmic process is given. The following are most critical to the process:

ASSERTION - a propositional belief entered into the system with an assigned belief value

DERIVED PROPOSITION - a propositional belief inferred from (an)other belief(s)

BELIEF - an assertion or derived proposition

ANTECEDENT - for a derived proposition P, any belief from which P is inferred in whole or part

DESCENDANT - for a given proposition P, any belief derived from P, in whole or part, through an inference

BELIEF VALUE - the degree of certainty of a belief, from 1 to 9 (see Figure 1)

- (positive belief values: 6 7 8 9)
- (negative belief values: 4 3 2 1)

BELIEF STATE - the state of a belief, based on its assigned belief value:

- (positive state: belief value {6 7 8 9})
- (negative state: belief value {4 3 2 1})
- (neutral state: belief value {5})

BELIEF CONTEXT - the belief values, antecedents, and descendants for a belief at a specific point in time

CHANGE IN BELIEF STATE - for a belief, the change from one state (positive, negative, or neutral) to another

STRENGTHENING OF BELIEF STATE - an increase in a positive belief value or a decrease in a negative belief value

WEAKENING OF BELIEF STATE - a decrease in a positive belief value or an increase in a negative belief value

CONTRADICTION - the attempted assignment of a positive belief value to a belief with a negative belief state, or vice versa

SUSPECT - for a contradicted belief, any of its antecedents; a suspect is considered possibly responsible for the change in belief state of the contradicted belief; a preliminary suspect has been implicated once in a contradiction, whereas a prime suspect has been implicated twice (a third implication leads to an accusation); suspects can still participate in the inferencing process, but at a weakened level of certainty

SUSPECT LIST - a list of all suspects and the contradicted beliefs for which they are considered possibly responsible

SUSPECTED-OF LIST - following a suspect in the suspect list, the list of contradicted beliefs for which the suspect is considered possibly responsible

The main algorithm for Belief Maintenance in the INFANT System is shown in Figure 2. The algorithm, which either changes, strengthens, or weakens a BELIEF, can be summarized as follows:

If BELIEF State changed:
If BELIEF not previously neutralized (ie, belief value not = 5):
- Save BELIEF context;
- Accuse BELIEF if it is suspected;
- Neutralize BELIEF's Descendants
  (recursive calls to Belief Maintenance);
- Suspect BELIEF's Antecedents
If a BELIEF context was saved and BELIEF's Antecedents are unchanged:
- Restore BELIEF and its Antecedents
If BELIEF State strengthened:
- Lessen suspicion if BELIEF suspected;
- Remove weaker Antecedents;
- Strengthen Descendants

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procedure Belief_Maintenance (BELIEF, new_belief_value)
begin
CASE
1. BELIEF state is changed:
   If old_belief_value NOT = 5 then
       begin
       Save current BELIEF context (remove any previously saved context);
       If BELIEF is a suspect, ACCUSE(BELIEF);
       For each descendant D (unless already updated for current input)
           Call Belief_Maintenance(D,5); {to neutralize D}
       For each antecendent A (unless already updated for current input)
           begin
             Remove A from antecendent list of BELIEF;
             Remove BELIEF from descendant list of A;
             Place A on suspect list as preliminary suspect
           end
           For each new antecendent contributing to the change in BELIEF's state
           Add to antecendent list of BELIEF
       end
   If an old context was saved for BELIEF then
       begin
       If no saved antecedents OR original belief state of saved antecedents = current belief state of saved antecedents then
           begin
           Restore saved context, taking belief value and antecedents from context
           (new or saved) that results in a strengthening of belief state
           For each saved antecedent A, remove A(BELIEF) from suspect list
           (and ACQUIT(A) if no longer a suspect);
           For each saved descendant D, Belief_Maintenance(D,nil); {to restore D}
           end
       end
2. BELIEF state is strengthened:
   If BELIEF a suspect:
       If BELIEF a preliminary suspect or new belief value 8 or 9 then
       ACQUIT(BELIEF)
       Else change BELIEF from prime suspect to preliminary suspect
   For each descendant D, strengthen D;
   For each antecendent A, delete A from BELIEF's antecedent list;
   For each new antecendent contributing to the change in BELIEF's state
   Add to antecendent list of BELIEF;
3. BELIEF state is weakened:
   If BELIEF a suspect then
       begin
       If a preliminary suspect, upgrade to prime suspect
       Else If a prime suspect, ACCUSE(BELIEF);
       end
   For each descendant D, weaken D;
ENDCASE
end

Figure 2 - The Belief Maintenance Algorithm
procedure ACCUSE (BELIEF)
If BELIEF is a preliminary suspect OR not a suspect then ASK for confirmation
Else
begin
Call Belief_Maintenance(BELIEF,5) {to neutralize BELIEF and its descendants}
Remove BELIEF from suspect list
For all contradicted beliefs X from suspected-of list of BELIEF do
begin
For all suspects B from the antecedents of X do
begin
    Remove B(X) from suspect list {ie, B is no longer suspected of X}
    If B's suspected-of list = nil then {ie, if B suspected of nothing else}
        ACQUIT(B)
end
end
end

procedure ACQUIT (BELIEF)
Remove BELIEF from suspect list
Set Revised-Antecedents to nil
For all contradicted beliefs X from suspected-of list of BELIEF do
begin
    For all suspects B from the antecedents of X do
    begin
        If B(X) exists then {ie, accumulate list of
        Add B to X's Revised-Antecedents
        end
        If Revised-Antecedents has one member B then {B is the only remaining suspect}
        ACCUSE(B)
    end
end

Figure 3 - ACCUSE and ACQUIT Algorithms

If BELIEF State weakened:
Increase suspicion if BELIEF suspected;
Weaken Descendants

Two additional algorithms are required, and are listed in Figure 3. The purpose of ACCUSE(BELIEF) is to ACQUIT any belief B whose suspected-of list is contained within BELIEF's suspected-of list (i.e., B is suspected only of contradictions that BELIEF was accused of). The purpose of ACQUIT(BELIEF) is to ACCUSE any belief B which remains the sole suspect in a contradiction of which BELIEF was acquitted.

4. An Example of the Belief Maintenance Process

Figure 4 shows the developing belief maintenance process for the monological conversational sequence

I do not like Bob.
He is the boy Joe plays with.
I know Joe is usually good to me.
I am not good to him, though.
But I like him.

In this section, a brief itemization of the steps involved in the process will be presented. It should be noted that all input statements are reduced to a Subject-Predicate-Object propositional form; additionally, whereas assertions are designated as
(a) I do not like Bob.  
He is the boy Joe plays with.

<table>
<thead>
<tr>
<th>Belief#</th>
<th>Belief</th>
<th>Value</th>
<th>Antecedents</th>
<th>Descendants</th>
<th>Suspect List</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I happy Bob</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Joe play Bob</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>I happy Joe</td>
<td>3</td>
<td>1 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>I near Joe</td>
<td>3</td>
<td></td>
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(b) I know Joe is usually good to me.

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<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>I happy Joe</td>
<td>6 (3)</td>
<td>3 (1 2)</td>
<td>2.2</td>
<td>1(2.1) 2(2.1)</td>
</tr>
<tr>
<td>2.2</td>
<td>I near Joe</td>
<td>5 (3)</td>
<td>(2.1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Joe good I</td>
<td>7</td>
<td></td>
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(c) I am not good to him, though.

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</tr>
<tr>
<td>2.1</td>
<td>I happy Joe</td>
<td>3 (6)</td>
<td>4 (3)</td>
<td>2.2 ()</td>
<td>3(2.1)</td>
</tr>
<tr>
<td>2.2</td>
<td>I near Joe</td>
<td>3 (5)</td>
<td>2.1 ()</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>Joe good I</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>I good Joe</td>
<td>1</td>
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(d) But I like him.

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<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>I happy Joe</td>
<td>7 (3)</td>
<td>3 (4)</td>
<td>(2.2)</td>
<td>4(2.1)</td>
</tr>
<tr>
<td>2.2</td>
<td>I near Joe</td>
<td>5</td>
<td>(2.1)</td>
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<td></td>
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<td>7</td>
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<td>I good Joe</td>
<td>1</td>
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Figure 4 - Successive Stages in the Belief Maintenance Process
elementary beliefs (e.g., Belief# 1, Belief# 2), derived propositions are designated as extensions of the beliefs from which they are derived (e.g., Belief# 2.1).

(a) I do not like Bob. (Belief# 1)
   He is the boy Joe plays with. (Belief# 2)

Figure 4(a) shows these beliefs as I happy Bob and Joe play Bob with belief values of 1 and 9, respectively. From these are derived the proposition I happy Joe 3 (Belief# 2.1), which reflects the probability that I am not happy with a person who plays with someone I don't like. Given the belief I probably not happy Joe, it follows that I probably not near Joe, and this derivation of Belief# 2.1 is subsequently recorded as Belief# 2.2.

(b) I know Joe is usually good to me. (Belief# 3)

The addition of this belief is shown in Figure 4(b) with a belief value of 7 (based on the adverb usually). Since in the INFANT System the proposition Joe good I implies I happy Joe, the previous belief value for the latter (descendant) proposition is adjusted to 6 (based on the algorithm in [7]) and the resulting change leads to the call Belief-Maintenance ('I happy Joe,' 6), which does the following:

1. Saves the current context for I happy Joe (Belief# 2.1): Belief Value (3), Antecedents (1 2), Descendants (2.2)
2. Calls Belief-Maintenance ('I near Joe,' 5) for descendant Belief# 2.2
   2a. Saves the current context for Belief# 2.2
   2b. Sets the new belief value for Belief# 2.2 to 5
3. Removes Belief# 3 from Antecedents
4. Removes Belief# 2.2 from Belief# 2.1 Descendants
5. Places Belief# 3 on the suspect list as a preliminary suspect
   (Beliefs 1 and 2 are 'suspected of' disbelief because of the change in Belief 2.1)
6. Removes Belief# 2.2 from Antecedents for Belief# 2.1 to 3

Beliefs 1 and 2 are suspected of involvement in the contradiction of I happy Joe (Belief# 2.1), and therefore will participate in further inferencing to only a limited degree. If the next input statement were I am not happy with Bob, Belief# 1 would be strengthened and thereby acquitted, the ACQUIT algorithm would then recognize Belief# 2 as the sole suspect in the contradiction of Belief# 2.1 and call Belief-Maintenance ('Joe play Bob,' 5) to effectively neutralize the accused belief and all its descendants.

(e) I am not good to him, though. (Belief# 4)

As a result of this input, the proposition I good Joe is added to Figure 4(c) with a belief value of 1. This new information causes yet another adjustment in the belief value of Belief# 2.1, from 6 to 3 (i.e., if I am not good to Joe then I am probably not happy with him). The steps performed by the belief maintenance call for Belief# 2.1 are as follows:

1. Saves the current context, removes the previously saved context
2. Removes Belief# 3 from Antecedents
3. Places Belief# 3 on the suspect list as a preliminary suspect in the contradiction of Belief# 2.1
4. Sets the belief value for Belief# 2.1 to 3
5. Sets the Antecedents for Belief# 2.1 to 4
6. Restores the saved context for Belief# 2.1
   6a. Restores Belief# 2.2 to Descendants
   6b. Adjusts the belief value to 3 and the Antecedents to Belief# 4; although the restoration of saved values (Antecedent Beliefs 1 and 2) would have likewise changed the belief value to 3, the stronger recent data is preferred
   6c. Calls ACQUIT(1) and ACQUIT(2); since the earlier contradiction of Belief# 2.1 has been reversed, Beliefs 1 and 2 are no longer suspects
   6d. Calls Belief-Maintenance('I near Joe,'nil) for descendant Belief#2.2
   6dl. Restores saved context for Belief# 2.2; the saved belief value of 3 and the saved antecedent (Belief# 2.1) are restored

Since only Belief# 3 remains on the suspect list at this point, the INFANT System will ask for a confirmation of its belief state (i.e., if I not happy Joe, is it still believed that Joe good I?)

(d) But I like him. (Belief# 2.1)

This input reasserts that I am happy with Joe (Belief# 2.1). Figure 4(d) shows the effects of the call Belief-Maintenance('I happy Joe,' 7), which generally reconstructs the context of Figure 4(b), with the exception that Belief# 4 is now considered the suspect in the contradictory state surrounding I happy Joe (Belief# 2.1). Again, as in the aftermath of Figure 4(c), the INFANT System may attempt to resolve the difficulty by questioning the believability of
the suspect information (i.e., if I happy Joe (Belief# 2.1), then is it still believed that I not good to Joe (Belief# 4) ?).

5. Conclusion

The nature of human reasoning leads to numerous difficulties in the attempt to automate the process of belief maintenance. Some are evident in the above examples, some are perplexingly subtle, and some are perhaps untreatable without significant changes to the present method. A few of the more troublesome issues can be described:

1. The contradiction of a derived proposition may be due to a faulty inference rather than to invalid assertions. Thus the inference itself is really to blame, and the assertions should not be considered suspects.

2. If a belief is uncertain (Joe is usually good to me), a number of questions arise:
   (a) Should it still be involved in the inferencing process?
   (b) Can it still be suspected in a contradiction and, if so, to what extent?
   (c) If previously more certain, are inferences previously derived from it (its descendants) affected?

3. A belief accused in one contradiction is presently considered responsible for other contradictions of which it is suspected. This may not be a valid assumption, for some other belief may be responsible.

These problems are being addressed cautiously as the development of the INFANT System continues. The system's goal is the development of a general-purpose model for the belief maintenance performed by a small child. The implemented model must produce reasonable, non-contradictory results. As with other implementations of complex processes, the effort must begin with examples that test the basic structure of the model, and then proceed to more problematic situations. Admittedly, the present model has been only partially implemented, and for rather simple examples. But the method utilizes an efficiently interlinked and cross-indexed knowledge base of suspects and supporting propositions that minimizes search requirements and maintains a record of context changes in its list structures, and thereby lends itself to continued expansion.

References