

# Belief Revision in Multi-Agent Systems

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**Abstract.** The ability to respond sensibly to changing and conflicting beliefs is an integral part of intelligent agency. To this end, we outline the design and implementation of a Distributed Assumption-based Truth Maintenance System (DATMS) appropriate for controlling cooperative problem solving in a dynamic real world multi-agent community. Our DATMS works on the principle of *local coherence* which means that different agents can have different perspectives on the same fact provided that these stances are appropriately justified. The belief revision algorithm is presented, the meta-level code needed to ensure that all system-wide queries can be uniquely answered is described, and the DATMS' implementation in a general purpose multi-agent shell is discussed.

## 1. INTRODUCTION

In many AI applications problem solving entities often have to make decisions based on partial, imprecise, and ever changing information. However in systems in which several agents cooperate with one another within a decentralised control regime, the information management problem is exacerbated still further - each agent has to contend with deficiencies and changes in the information supplied by its contemporaries as well as in its own local information.

To keep track of an agent's changing beliefs, researchers have devised a number of different types of Truth Maintenance System (TMS) [1]. Such systems portray as their main features the maintenance of the coherence between their beliefs, the reason for their beliefs and the identification of contradictions. Whilst these systems are generally sufficient for maintaining beliefs in an asocial context, they need to be extended if they are to be used in a social context. For example, as well as beliefs that an individual has generated for itself, there will be beliefs that it has been informed about by other community members (either because an acquaintance has answered a query or because it has volunteered a piece of relevant information). In such cases a number of crucial decisions must be made about how the information provided by other agents should be treated - should it be given the same credence as locally deduced beliefs?, should it only be used when there is supporting local evidence?, how should contradictions between the beliefs of different agents be dealt with?, and so on. It is in the discussion and resolution of these issues (section 2), and their subsequent implementation (section 3), that the main contribution of this work lies.

## 2. REVISING BELIEFS IN MULTI-AGENT SYSTEMS

This section briefly describes the fundamentals of belief revision systems (section 2.1), before the key principles and concepts of belief revision in multi-agent systems are expounded (section 2.2).

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ECAI 94. 11th European Conference on Artificial Intelligence. Edited by A. Cohn

Published in 1994 by John Wiley & Sons, Ltd.

### 2.1 Asocial Belief Revision

In a TMS "belief" is taken to mean justified belief - either it is an assumption or it has been deduced from other beliefs. An assumption is always believed; an ordinary fact may be believed or unbelieved; and a contradiction is always false. There are a number of different ways in which the dependencies between beliefs can be registered: in justification based TMSs (JTMSs) each belief is associated with the beliefs that immediately caused it [2]; whereas in an assumption based TMS (ATMS) each belief is associated with the smallest set of environments from which it can be deduced (the *belief's label*) [3]. This work concentrates on the ATMS approach because, when compared with the JTMS, it:

- enhances the system's efficiency and improves its real time operation because multiple contexts are kept (This makes it faster to move from one valid context to another because the new one does not have to be calculated from scratch);
- improves the system's transparency because the belief revision is not contingent on dependency oriented backtracking and hence it will not stop on unresolved circularities or leave nodes unlabeled.

ATMS's are composed of three units: (i) the truth maintenance system itself; (ii) the problem solver; and (iii) the interface unit. The TMS guarantees that the conclusions reached by the problem solver are kept updated and coherent. However it only deals with propositions (usually substituted by arbitrary identifiers called nodes) and their dependencies. For each proposition there will be a node and for each dependency a justification which describes how the node was deduced from other nodes. The TMS has three basic operations: (i) create a new *assumption node* whenever new propositions are assumed to be true; (ii) create a new *ordinary node* when a new proposition is deduced by the problem solver; and (iii) add a new justification to an existing node whenever the problem solver finds a new way of deducing it.

While a conventional rule-based problem solver generally develops a unique solution, a reasoning system with an ATMS determines the whole set of possible solutions. This different operating mode necessitates the adoption of a different problem solving methodology and a different knowledge representation. The rules have to be transformed into sets of unit steps called *consumers*. This transformation includes the calculation of the consumer's depth which indicates its dependence. The greater this depth, the greater the consumer's dependence on others (i.e. execution of a consumer of depth D can only be done after the D-1 depth consumers have been executed, and so forth). Using this depth information, the problem solver chooses the nodes according to the number of assumptions they depend on, starting with the nodes with the fewest assumptions. A consumer is triggered only when the ATMS holds valid justifications for each of its precondition nodes; once fired, it converts itself into a justification of the conclusion node and ceases to exist as a consumer. The set of consumers to be executed at any given time can be obtained through

a scheduling algorithm [4] and an agenda which contains every node with a non empty label and pending consumers. The problem solver repeatedly chooses one of these consumers, executes it, and then removes it, until there are no nodes left on the agenda.

The main purpose of de Kleer's algorithm is to find, as efficiently as possible, the most general environment of a node and the most general version of a contradiction. Adopting this strategy avoids unnecessary work since: (i) by finding the most general version of a contradiction it avoids various solving steps which would only lead to inconsistencies; (ii) by finding the most simple node label it avoids superfluous label updating. This approach guarantees that the consumers of the antecedent nodes will always be scheduled before the node's own consumers. The main cycle consists of choosing the consumer with the smallest consistent environment, running it, and then removing it. With such an agenda, the ATMS-problem solver combination will always find the most simple labels first - identifying all possible solutions with the least effort.

The final component of the ATMS is the interface unit which supports the following functionalities: assumption creation; node creation; addition of justifications; and querying about beliefs.

## 2.2 Locally Coherent Multi-Agent Belief Revision

Global coherence in a distributed belief revision system means complete coherence between all of the agents' conclusions all of the time. However attainment of this level of coherence depends not only on the system's architecture and design but also on the amount of inter-agent communication which is acceptable. Whenever a centralized architecture is appropriate it is reasonable to build a global TMS which incorporates all of the system's facts and justifications; whereas in the case of a distributed architecture a pragmatic compromise between the achieved coherence level and the information redundancy among the agents has to be reached. These two architectural options give rise to two fundamental approaches to belief revision in a multi-agent system: respectively, *global coherence* and *local coherence*. In the first case, two or more agents cannot assign a different belief status to the same fact. In the second case, different agents may have different perspectives over the same fact if conveniently justified.

In multi-agent systems the autonomous agents each have their own repositories where they record local propositions and justifications. Only when cooperation occurs do nonlocal facts have to be represented. In such an environment global coherence is unattainable, unless the system broadcasts every relevant activity to all the pertinent agents, therefore we settled for local coherence. Given this stance, the question of how to include external propositions in an agent's local dependency network becomes a crucial issue. Depending on the scheme chosen for attaining local coherence, an agent that receives an external fact may or may not receive its label: if the label is sent, it is possible to guarantee the coherence between the foundations of the external fact and the local facts and assumptions; if no label is sent, it is impossible to cross check the external fact's foundations with the local TMS data. In the first case the agents exhibit *local-and-shared well-foundedness* and local coherency, whilst in the second case there is only *local well-foundedness* and local coherency [5]. We chose the latter because it is more appropriate for modelling autonomous agents which have their own beliefs, desires and intentions. Consequently, the community of agents behaves like a democratic society in which each individual can hold a different opinion once it is locally justified - an agent only accepts to revise its beliefs based on external information when it does not have its own convictions regarding that fact.

Using this scheme, a given agent's knowledge has to be divided into two separate sets:

- *private beliefs* that the agent has generated and kept to itself
- *shared beliefs* that the agent has in common with at least one acquaintance.

Within a particular agent, a shared belief can either be *internal* (endogenous) or *external* (exogenous). The former means that the agent has deduced the fact for itself; the latter means that the agent has received the information from an acquaintance. This classification is central to the belief revision process because:

- private beliefs have a local scope and are automatically revised by the agent's ATMS
- shared beliefs are revised only by the agent that created them (i.e. agents where the beliefs are classified as shared internal). The revision action is performed by the originating agents' ATMS module and then the updated beliefs are resent to all the acquaintances where they are known as shared external.

The basic operation of each agent can be described as a continuous loop of: (i) receiving and processing new beliefs; (ii) updating the items on the agenda; (iii) executing its agenda. Whenever a fact is presented to the system (through the user agent) it is immediately routed to the appropriate agents. The recipients are those agents where the fact has been, or can be, assumed or deduced. Once the arrived fact has been locally revised it is sent to all of the acquaintances where the necessary updates take place. The belief revision algorithm followed by each agent is given in more detail in figure 1.

This algorithm does not guarantee that a unique belief status will be attributed to every shared belief. If the domains of several agents overlap, then a shared belief can be internal to several community members. In such circumstances, whenever a belief revision occurs in any of these agents, the system may find that the same belief has a different belief status in different agents. The way in which the agents that rely on such shared external beliefs decide which belief status to adopt is explained in section 3.3.

## 3. IMPLEMENTING LOCALLY COHERENT MULTI-AGENT BELIEF REVISION

The aforementioned multi-agent belief revision algorithm has been implemented in a general purpose system which facilitates cooperation between autonomous problem solving agents. The agents themselves are divided into two distinct functional units: a domain level system and a cooperation layer. The former is implemented as an assumption based belief revision system and contains, among others, domain expertise on planning and scheduling (section 3.1). The latter is the interface between the agent and the rest of the community and provides the necessary facilities for establishing, maintaining and monitoring cooperation (section 3.2).

### 3.1 Implementing Distributed Belief Revision

As a first step, the rules and facts of the domain level system's knowledge base are transformed into consumers and nodes (which have the following knowledge representation):

- `consumer (Dep, Id, List_of_Antecedents, Consequent)` in which `Dep` stands for depth, `Id` for the identification of the rule that originated that specific consumer, `List_of_Antecedents` contains the precondition nodes list and `Consequent` contains the conclusion node.

```

IF a fact F has arrived at AGENT THEN
  IF F EXISTS IN AGENT THEN
    IF SHARED-EXTERNAL(F) THEN
      IF F's status is unbelieved or false & it is currently believed by AGENT
      THEN invoke ATMS to remove assumption that represented F and create an ordinary node
        with an empty label
      IF F's status is believed & it is currently unbelieved by AGENT
      THEN invoke ATMS to remove the ordinary node with an empty label that represented F
        and create an assumption
    IF SHARED-INTERNAL(F) THEN
      IF F's new status ≠ AGENTs current belief status THEN invoke ATMS in standard manner
  IF F DOES NOT EXIST IN AGENT THEN
    IF F's belief status is unbelieved/false THEN create ordinary node with empty label
    IF F's belief status is believed THEN create an assumption

```

After this processing, the agent updates its own agenda and executes it. For every node in the agenda the ATMS is invoked in the standard manner, that is:

```

IF node has pending consumers & node's antecedents are believed
THEN incoming node's justification is sent to ATMS

```

Finally, if any shared internal nodes are revised during these actions then their incoming belief statuses are sent to the relevant acquaintances.

Figure 1: The Agents' Belief Revision Algorithm

- `node(Datum, Class, Type/Index, Scope, Agent)` where Datum is the proposition the node represents, Class specifies whether the node is an assumption or a deduced node, the third argument, if the node represents an assumption, contains its index, otherwise it specifies the deduced node type, Scope specifies whether the proposition is local, shared internal or shared external, and Agent contains the name of the agent responsible for having deduced the node.

### 3.2 Implementing the Cooperation Layer

The functionality related to cooperation is represented as a distinct problem solving layer which sits above the ATMS-problem solver component (figure 2). The cooperation layer has the following components [6]: a cooperation module; a communication module which sends/receives messages between/from the agents; a self model which represents information about the underlying domain level system; and a set of acquaintance models which represent the relevant information about the other community members with which the agent can be expected to interact.

The Cooperation Module is responsible for determining when cooperation is necessary and for deciding what strategy should be employed for each social interaction. Cooperation can be viewed from two perspectives: from the *organiser's* point of view and from the *respondent's* point of view [7]. The organiser starts the cooperation based on its needs and views. This includes asking for assistance (*task sharing*) and supplying voluntary help (*result sharing*). Task sharing is initiated when the organiser has an activity that it cannot accomplish alone and so it looks for help within the community - the agent which accepts the task is the respondent. Result sharing is initiated when the organiser generates information which it believes will be useful to others, based on its acquaintance model, or if it has revised some of its shared beliefs.

The Communications Module provides the necessary physical channels and the high-level protocol needed to support cooperative

problem solving. The implemented system is based on message passing through the UNIX Operating System sockets. The high-level protocol is based on speech act theory [8] and has the following primitives:

- `request(Organiser, Respondent, Data)`: Organiser asks the Respondent for help in producing Data (task sharing).
- `query(Organiser, Respondent, Data)`: Organiser queries the Respondent about a belief.
- `answer(Respondent, Organiser, Data)`: Respondent answers a request within framework of a task sharing cooperation.
- `assign(Organiser, Respondent, Data)`: Organiser initiates result sharing cooperation action as result of some shared beliefs' revision.
- `reply(Respondent, Organiser, Data)`: Respondent answers a previous query about a belief.
- `explain(Respondent, Organiser, Data)`: Respondent explains the reason for a particular belief, e.g., provides its foundations.

In order to participate effectively in a multi-agent system, an agent must know which of its tasks can be carried out without assistance (*independent tasks*) and which of its tasks depend on other agents in some way (*dependent tasks*). This information is represented in the agent's self model: `who_am_i` gives the agent's identification; `my_conclusions` gives the tasks the agent is capable of performing; `i_know_about` gives the facts the agent knows about; and `my_goal` gives each task's requirements and results.

The acquaintance models provide agents with information about who can assist them with their dependent tasks (`who_knows_about`) and who they can assist by volunteering useful information (`is_interesting_to`).

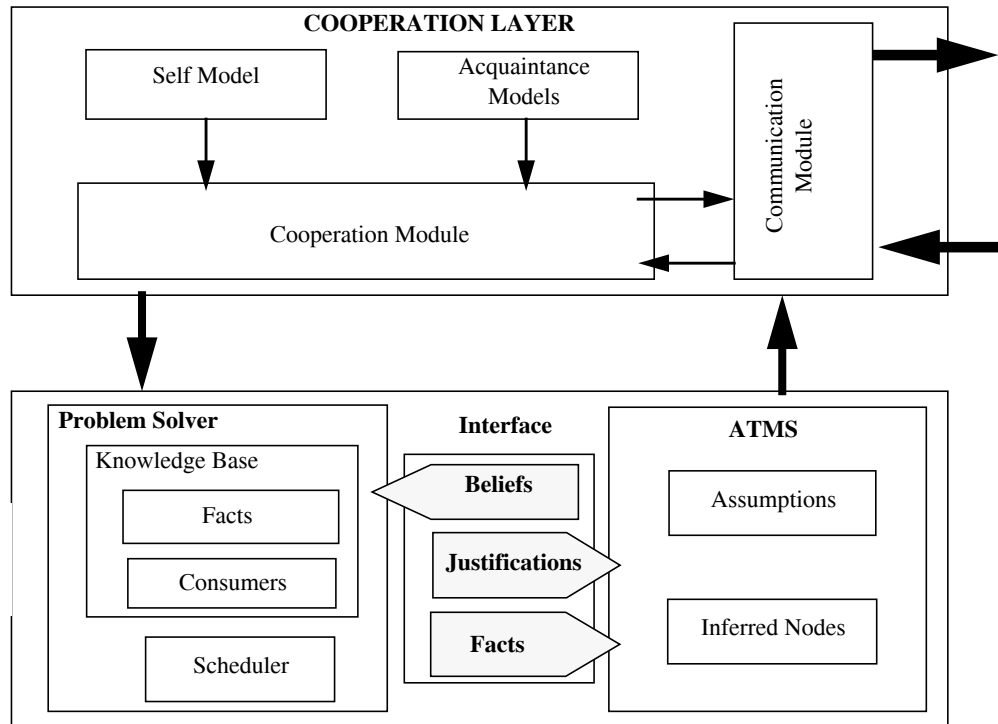


Figure 2: Agent Architecture

### 3.3 Cooperative Problem Solving

A cooperative interaction is started: (i) when an agent needs assistance; (ii) when an agent is able to supply help; and (iii) when a belief revision of shared knowledge occurs. An example of each of these cases is presented below:

#### i) Task Sharing Cooperation:

Agent<sub>1</sub> requests help from agent<sub>2</sub> to determine whether michel is a member of staff. Agent<sub>1</sub> knows that it is unable to produce this information, by examining the `my_conclusions` slot of its self model, but the `who_knows_about` slot of its acquaintance model indicates that agent<sub>2</sub> can assist in this activity.

```
request(agt1, agt2, staff-michel)
```

If agent<sub>2</sub> can deduce that michel is a member of staff it will answer agent<sub>1</sub> by sending the corresponding belief status (eg believed).

```
answer(agt2, agt1, staff-michel-believed)
```

Then the already detailed belief revision algorithm is locally triggered at agent<sub>1</sub> with `staff-michel-believed` as a shared external fact.

#### ii) Result Sharing Cooperation:

Agent<sub>1</sub> voluntarily sends a result (eg that john is believed to have been promoted) to agent<sub>2</sub>. This exchange occurs because agent<sub>1</sub>'s model of agent<sub>2</sub> states in the `is_interesting_to` slot that john's promotion is a relevant piece of information.

```
assign(agt1, agt2, promoted-john-believed)
```

Then the already detailed belief revision algorithm is locally trig-

gered at agent<sub>2</sub> in order to incorporate this new proposition as a shared external fact.

#### iii) Belief Revision of a Shared Fact:

(a) Agent<sub>1</sub> no longer believes in the internal shared fact that john has been promoted and through consulting its acquaintance models (the `is_interesting_to` slot) it passes this information onto agent<sub>2</sub>.

```
assign(agt1, agt2, promoted-john-unbelieved)
```

(b) Agent<sub>2</sub> no longer believes the internal shared fact that michel is a member of staff and through consulting its acquaintance models (the `is_interesting_to` slot) it passes this information to agent<sub>1</sub>.

```
assign(agt2, agt1, staff-michel-unbelieved)
```

Then, in both cases, the already detailed belief revision algorithm is locally triggered at the respondent in order to update the corresponding shared external belief.

The adopted architecture results in locally responsible agents that provide the community with local coherence. However, this approach still leaves some important questions unanswered: what does the system answer when it is queried about a fact for which different agents have a different belief status? and what belief status will be adopted by an agent that has represented such a shared external fact? With respect to the first question, there are two possible situations:

- the fact under analysis is part of a contradiction, regardless of the agent
- the fact under analysis is not part of a contradiction.

In the first case, the system answers that the fact is part of a contradiction and therefore it is false; in the second case, if there is at least one agent that has reason to believe in the fact, the system answers the query by stating that the fact is believed. Essentially the same mechanism has also been adopted to solve the second question of deciding in which acquaintance an agent should believe. Some meta-level code is placed on top of the already described belief revision algorithm to act as a filter for the incoming data:

```

IF incoming fact F is a new fact
THEN call standard belief revision algorithm
IF F already exists THEN
  IF the incoming belief status is originated
  by the current owner of the fact
  THEN revise F accordingly
  IF the incoming belief status is false (F
  is part of a contradiction to some agent)
  THEN revise F accordingly (becomes false
  and will be owned by the agent that
  found the contradiction)
  IF the agent's belief status for F is
  unbelieved & the incoming belief status
  is believed
  THEN revise F accordingly (unbelieved to
  believed)

```

#### 4. CONCLUSIONS

This paper outlines the key issues associated with belief revision in multi-agent systems and describes how a locally coherent cooperating community can be designed and implemented for a real world scenario. The adopted implementation platform, which was originally conceived as a general purpose multi-agent architecture supporting different forms of cooperation [6], also turned out to be well suited for supporting belief revision activities. The knowledge contained in the cooperation layer's models ensures that if a change occurs in an existing domain level system fact it will be communicated to every agent where it is external, additionally the models ensure that incoming facts are always communicated to the relevant agents. Belief revision is attained not only through the implementation of the distributed ATMSs but also through the addition of meta-level control actions which guarantee a unique justified answer to every query (with a time response which is adequate for the majority of real world applications).

To put this work in context we briefly compare and contrast it with two of the most important distributed belief revision systems which have been developed to date. Mason and Johnson implemented a Distributed ATMS where the interchange between the agents includes not only the shared data, but also the shared data labels and the invalid assumptions sets [9]. They present agents which exhibit local and shared well foundedness (the foundations of the incoming facts are cross-checked with the local assumptions in order to guarantee that these foundations are not locally disbelieved) as well as local coherence. In our system, the agents exhibit only local well foundedness; when we decided not to send the label together with the node's belief status we deliberately dropped the possibility of guaranteeing the shared facts well foundedness in order to gain a computational speed up. To compensate we apply the following methodology throughout our system: (i) every answer provided by the system is inspected in order to verify that it does not contain any of the system's detected contradictions; (ii) before

adopting or updating a shared external belief the receiving agent collects all of its different perspectives, and only then asserts its status, based on the results of the described meta-level control actions.

Huhns and Bridgeland implemented a distributed JTMS that provides local and shared coherence [5]. Their system suffers from the typical JTMS problems: computational overhead (not suitable for real world applications) and possible unsatisfiable circularities. In addition their implementation allows an agent with less information to dominate a more knowledgeable agent and their system is "agnostic about what data should be shared among agents".

For the future, we are investigating how our Distributed ATMS implementation can be applied in the domain of geographical information systems. On the theoretical side a number of issues require further investigation, these include: explicit negation and more sophisticated conflict resolution policies.

#### ACKNOWLEDGMENT

This work has been supported by the British Council / JNICT Protocol Grant 423.

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